Optimising cycle frequency: The effects of imposed cycle frequency training on the coordination and performance of skilled age-group swimmers.

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DECLARATION

Thesis submitted for the degree of Doctor of Philosophy to The University of Edinburgh.

I hereby declare that this thesis is my own work, that it has not been submitted for any other academic award, or part thereof, at this or any other educational institute.

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ABSTRACT

Purpose: Underwater undulatory swimming (UUS) is a fundamental skill incorporated during the starts and turns of three of the four competitive swimming strokes. Significant competitive advantage can be gained if UUS performance is optimised. The cycle frequency adopted during UUS in both animal and human swimmers have been extensively studied and it has been shown to have a strong relationship with the UUS velocity (U) achieved. The purpose of this thesis was to investigate the changes in performance and coordination in UUS which occur as a consequence of training at an imposed cycle frequency (identical to preferred) in skilled age-group swimmers (Study 3). To achieve the stated purpose, the reliability (systematic bias, within-subject variation and test-retest reliability) of the kinematic variables commonly used to describe and analyse UUS were established (Study 1). Once reliability was determined, the key kinematic performance and coordination variables in relation to the production of maximum U were identified (Study 2) to enable the key measures of performance and coordination to be monitored in response to a training perturbation (imposition of a cycle frequency) in the final study. **Methods**: Measures of systematic bias, within-subject (WS) variation and inter-class correlation (ICC) of nineteen kinematic variables were determined over four sessions. This was undertaken to establish the requirement of any familiarisation training, number of cycles of data required to provide an accurate representation of each variable when reporting a mean value, and the related variability associated when reporting mean values based on a set number of data cycles (Study 1). Backward elimination ANCOVA statistical models with participant as a fixed-factor were employed to establish which of the performance and coordination variables

were best in explaining the variance of cycle frequency, cycle length (CL) and ultimately *U* (Study 2). In the final study (Study 3) the performance and coordination variables identified from study 2 were analysed in sixteen skilled age-group swimmers which participated in a randomised controlled study. An experimental group of eight participants completed a four week imposed frequency (matched to their own preferred frequency) training programme, while a control group of eight participants completed a four week programme training at a self selected preferred cycle frequency. The UUS kinematics for both preferred cycle frequency UUS and imposed cycle frequency UUS were measured at weekly intervals throughout the training period. An additional retest (RT) was conducted 2 weeks after the cessation of the training period. **Results**: Systematic bias was identified between the 1st and the remaining 3 testing sessions for cycle frequency, CL and *U*. The minimum number of data cycles required to achieve an acceptable measure of retest reliability (ICC >0.85) across all kinematic variables was 6 cycles. At 6 cycles WS variation ranged from 0.86 to 8.92 %CV. A total of 10 kinematic variables were identified as key to explaining the variance in cycle frequency and CL. A final parsimonious ANCOVA model revealed that 2 variables (maximum knee angle velocity and wave velocity between knee and ankle) explained a large proportion (Adj. $r^2 = 0.944$) of the variance in maximal *U*. However, when the participant was removed as a fixed factor the explained variance reduced (Adj. $r^2=0.535$). No significant difference in maximal *U* was found over the training or RT period. No variables were found to differ significantly by Session x Frequency Tested x Training Group ($p<0.01$). However, several discrete kinematic variables and measures of coordination showed statistically significant changes, either between Frequency Tested or across testing

sessions. **Discussion**: After determining the systematic bias and establishing the requirement for a familiarization session, 6 cycles of data were found to be sufficient to provide high levels of reliability for each of the UUS kinematic variables. The identified key determinants of the variance in cycle frequency, CL and maximal *U*, revealed that the successful transmission of the propulsive waveform along the caudal aspects of the swimming body (specifically the kinematics/coordination at or around the knee) and the control of the shedding of the vortices and simultaneous recapture/reuse of previous shed rotational energy are key discriminating factors between the faster and slower UUS in skilled age-group swimmers. The 4-week training period did not result in changes in maximal *U* for either of the training groups. However, there were significant differences in the magnitude and process of adaptation between preferred and imposed frequency training groups' kinematics and measures of coordination over the training and testing period. The importance of each individual's own solution to the maximal UUS problem was highlighted, with coordination constrained by an individual's own idiosyncratic constraints. Further research is required to establish the efficacy of the imposition of a cycle frequency identical to an individual's own preferred frequency as an appropriate training modality for maximal *U*. In conclusion, the present research provides valuable insight into the effects of the simple act of cycle frequency imposition, providing a baseline for future cycle frequency interventions which take place at higher/lower cycle frequency or over longer training periods.

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Chapter 1

Introduction

1.0 Introduction

The optimisation of performance can be regarded as *the* fundamental goal for both athlete and coach. The concept of performance optimisation in cyclical sporting activities (running, cycling, rowing, swimming, etc) is a complex one, having many facets which need to be considered and addressed in order to enable a skilled athlete to improve their performance. It must first be understood that the *optimisation* of performance is a process; a continual evolution and adaptation of the interrelated factors involved in the execution of a particular action to improve performance. As such, knowledge and understanding of the key components involved in the performance of the action and the process by which adaptations and evolutions in coordination and performance occur are paramount for the successful optimisation of performance.

A popular topic for cyclical activity research is UUS. The vast majority of research undertaken to examine undulatory forms of aquatic locomotion have focused on aquatic animals. In the animal UUS research, the end-effector cycle frequency with which the swimming action is performed has been shown to be strongly related to the swimming velocity achieved (Bainbridge, 1958; Hunter and Zweifel, 1971; Fish, 1984; Long *et al.*, 1994). Also, it has been verified that higher cycle frequencies correspond to faster swimming velocities (Hunter and Zweifel, 1971). While the modelled relationship between cycle frequency and swimming velocity has been shown to have a linear relationship over the velocities tested (Fish, 1984; Long *et al.*, 1994), it is important to recognise that a number of interrelated factors have to be coordinated at any given cycle frequency to produce a maximal UUS velocity.

Maximal UUS velocity is produced via the sequenced oscillations of sections of the body creating bends along its length, which generate an undulatory wave, transferring momentum to the water to produce a propulsive impulse (McHenry *et al.*, 1995). The movements employed to generate the propulsive forces required for UUS act simultaneously to produce a large proportion of the resistive forces (active drag) experienced (Ungerechts, 1984). Understanding that active drag (AD) is altered as a consequence of changes in shape and size of the swimming body (with respect to the direction of flow), it becomes evident that UUS velocity maximisation is more complex than simply striving to increase cycle frequency. As the UUS body is required to coordinate the amplitude and timing of these oscillatory movements to maximise the UUS velocity by simultaneously optimising propulsive and resistive forces, an understanding of the process by which swimmers learn to coordinate the spatial and temporal characteristics of these movements to produce a maximal UUS velocity is essential.

1.1 Defining cycle frequency

The cycle frequencies adopted by skilled performers during cyclical movement tasks, have been the focus of much research (Brisswalter *et al.*, 2000; Goosey *et al.*, 1999; Kaneko, *et al.*, 1987; Neptune & Hull, 1999; Pelayo *et al.*, 1997; Sparrow, *et al.*, 1999; Swaine & Reilly, 1983; Van Emmerik *et al.*, 1989). The general consensus within the above research is that maximal performances are obtained when skilled athletes employ self-selected preferred cycle frequencies, i.e. freely adopted cycle frequencies which are allowed to vary over time.

The optimisation of performance has been examined in terms of the generation of maximum power output, its relationship with the modelled resonant frequency of a system, and/or the coordinative strategies employed to elicit an optimal performance. Sparrow (1983) advocated that for many tasks the preferred cycle frequency is the most efficient, suggesting that at the preferred frequency the physiological characteristics of the muscles become optimally organised. Sparrow (1983) also stated that frequencies other than the preferred frequency interrupt the organisation of the muscles/muscle groups, making the system less efficient and detrimental to performance. The ideas presented by Sparrow (1983) concur with those of Bach *et al.* (1983) and Lindstedt *et al.* (2002), which indicated that for many activities, skilled performers naturally adopt cycle frequencies which both maximise energy return and minimise energy loss from the muscle to optimise performance in cyclical activities at both maximal and sub-maximal levels. Thus, the performer may be seen to be operating at or around the system's resonant or natural frequency when performing specific movements. However, these findings are not without contention.

Previous examinations of the relationship(s) between preferred cycle frequency and performance of both skilled and unskilled performers have focused consistently on changes in coordination, performance and/or economy/efficiency over a range of higher and/or lower cycle frequencies with minimal familiarisation training (Marais and Pelayo, 2003). It has also been implied that the preferred cycle frequency is representative of an 'optimal' cycle frequency (Marais and Pelayo, 2003). Determining 'optimal' cycle frequency in this manner assumes a static relationship between preferred cycle frequency and performance, and is not congruent with the

concept of a process. This static relationship limits the practical implications of the research findings; with this research design presenting only a 'snapshot' of the interaction between an individual's preferred cycle frequency and the requirements of the task. This design does not account for the ability to adapt and evolve in response to changes in task, organismic and/or environmental constraints.

Therefore, understanding that performance optimisation is a dynamic process undergoing a continual evolution, the suggestion that an individual's preferred cycle frequency (at a particular instant in time) is representative of their optimal cycle frequency is inconsistent with the concept of a process and may not afford insight of how a better solution to the movement problem can be achieved. It should be considered that there may be other solutions at different cycle frequencies which afford higher levels of performance once the system has adapted itself to a *new* cycle frequency and/or altered the patterns of coordination at an already established preferred cycle frequency. This represents a fundamental principle of the coaching and training process, as performers seek to actively manipulate the organismic constraints and their interaction with the task constraints, which dictate the preferred cycle frequency achieved. To explore this process the dynamical systems theory (DST) can be utilised. A DST perspective of the coordination and development of a cycle frequency for optimising performance is framed by a process of self-organisation of the movement system that emerges from within the organismic, task and environmental constraints (Newell, 1991). The processes involved in learning to maximise performance require the individual to search and explore the perceptual-motor workspace defined by the action boundaries provided by the interacting

organismic, task and environmental constraints (Newell, 1991). Given the recognised importance of cycle frequency to the production of maximal UUS, an understanding of how the imposition of cycle frequency affects skilled swimmers' coordination and performance throughout the duration of any intervention designed to alter a swimmers UUS performance, is fundamental to understanding this process of optimisation.

1.2 The efficacy on an imposed cycle frequency

The efficacy of the methods by which performers are encouraged to search the perceptual-motor workspace, to find increasingly effective and efficient solutions to the motor problem remains a pressing question for researchers, coaches and athletes. Due to the complex interactions and overwhelming number of degrees of freedom (DoF) apparent in the actions of skilled performers, some researchers have attempted to grasp the fundamentals of coordination and the effects of an imposed cycle frequency by limiting the research to the investigation of '*simple*', highly constrained, non *'real world'* tasks such as finger tapping or waggling (Newell, 1991).

While the use of single DoF tasks and the restricted amount of practice routinely employed in these types of studies provided a fundamental understanding of the underlying process of motor control, they are limited with regard to enabling direct understanding of the process of optimisation in more complex movement systems (Newell, 1991). In addition, research has tended to focus on cycle frequency, coordination and performance in isolation, examining either the variations and stability of coordination or the difference in performance relative to changes in cycle

frequency (Smoll and Schultz, 1982; Swaine and Reilly, 1983; Neptune *et al.,* 1997; Goosey *et al.,* 2000; Martin *et al.,* 2000; Marais, Dupont, *et al.,* 2002). In addition, these studies have been limited to (i) the use of non *real world* tasks, which by implication use measures of performance that are selected arbitrarily (Haken *et al.,* 1985;); (ii) an analysis of an end-effector/single anatomical point as representative of the coordination of the human movement system (Nourrit *et al.,* 2000; Lay *et al.,* 2002), (iii) a focus on sub-maximal tasks (Sparrow, 1983; Sparrow *et al.,* 1999), or (iv) the initial learning stages of novices (Delignieres *et al.,* 1998).

Furthermore, previous motor control and motor learning investigations of complex behaviour of skilled performers have either (i) involved comparisons between novice and expert performer coordination (Temprado *et al.,* 1997; Delignieres *et al.,* 1998; Cordier *et al.,* 1994), (ii) examined pre-test v post-test measure of coordination after a designated training intervention period (Bootsma *et al.,* 1991; Anderson and Sidaway, 1994, Goodway, *et al.,* 2002); or (iii) assessed changes in coordination with minimal familiarisation/training period (Van Emmerik *et al.,* 1989). Both Newell, (1991) and Nourrit, *et al.* (2003) proposed that neither novice/expert or pre/post test comparisons fully explain the learning/transition process, and as such have a limited value when trying to understand the dynamics of any coordination changes. Newell (1991) also stated that the qualitative shifts in the coordinative strategies employed by skilled performers which occur as a function of practice, and the flexible and adaptive qualities of the skilled performers are rarely studied. With the exception of research such as Sanders (1998) very little has been undertaken to examine the

effects of any type of extended training intervention on the changes in coordination of skilled performers.

Van Emmerik *et al.* (1989) examined the effects of training in novices learning to ski on a simulator at (i) a preferred cycle frequency, (ii) an imposed preferred cycle frequency which was determined from a modelled relationship between weight and frequency, and (iii) higher and (iv) lower imposed cycle frequencies. Van Emmerik *et al.* (1989) found that the preferred cycle frequencies (self-selected and imposed) represented the most effective ways in which performance/learning was optimised, compared to learning at higher and lower imposed cycle frequencies. The research by Sparrow *et al.* (1999) and Van Emmerik *et al.* (1989) also provided support for an earlier idea proposed by Smoll and Schultz (1982) that training at imposed cycle frequencies (higher and lower than the preferred frequency) can serve to reduce the initial detrimental effects in performance associated with operating at a frequency above or below the preferred frequency.

Both Sparrow *et al.* (1999) and Van Emmerik *et al.* (1989) found that performance at imposed (higher / lower) cycles frequencies did improve with a limited amount of practice, but not to the extent of the performance levels achieved at a preferred cycle frequency. Whilst this supports the proposal of Sparrow (1983) that the muscles are optimally organised at a preferred cycle frequency; the improved performance with minimal training at imposed frequencies suggests that further research is required to fully examine the impact of more realistic training periods at an imposed cycle frequency.

Importantly, there is a dearth of research examining the effects of frequency imposition, i.e. the effects on coordination and performance of the act of 'imposing' and training at a cycle frequency identical to a performers' preferred cycle frequency. Therefore, questions remain regarding the efficacy of imposing the self-selected preferred cycle frequency of a skilled athlete. Could training at an imposed preferred cycle frequency actually serve to improve the performance of a skilled athlete? Conversely, could training at an imposed preferred cycle frequency interfere with established preferred cycle frequency coordination and decrease UUS performance levels, or even act to limit the search for a more optimal solution to the motor problem? Furthermore, questions remain as to the process by which any changes in performance and/or coordination occur as a function of an imposed cycle frequency training programme. Consequently, it is apparent further examination is required to understand the relationships between a preferred cycle frequency, the act of 'imposing' and training at an imposed preferred cycle frequency and the process of optimising cycle frequency in skilled athletes.

To date, no research has established the reliability of the variables commonly reported in UUS. The determination of the reliability of the commonly reported variables is required to ensure that any changes observed which occur as a consequence of an intervention can be identified as being outside the within-subject variation levels associated with the UUS task. Therefore, prior to an examination of the effects of the imposition of a cycle frequency on the UUS of skilled age-group swimmers, the reliability of the kinematic variables concerned with the execution of maximal UUS would need to be determined. In addition, the relative importance of

each of the large number of variables which have been examined in previous studies of UUS would need to be established. The identification of key kinematic variables and measures of coordination with respect to their ability to predict UUS performance is also required. Analysing these key variables would enable a comprehensive analysis of the effect of training at an imposed preferred cycle frequency, and provide empirical evidence to determine the efficacy of any measures of coordination utilised to examine UUS system dynamics.

1.3 Statement of Purpose.

The purpose of the present research was to (1) determine the reliability of the kinematic variables of UUS, (2) identify the key kinematic variables and measures of coordination, and (3) investigate the effects of the act of 'imposition' and efficacy of four weeks training at an imposed preferred cycle frequency for improving UUS performance in skilled age-group swimmers. Therefore, to address the identified purposes, three studies were undertaken:

Study 1: Reliability of kinematic variables in maximal undulatory underwater swimming.

Aims:

(1) Determine the extent of any systematic bias between session, trial and/or cycle.

(2) Establish the within subject variation of the key biomechanical measures commonly used to assess maximal UUS performance in skilled swimmers.

(3) Ascertain the number of cycles/trials required to obtain stable levels of variability and high levels of reliability in the maximal UUS kinematics.

Study 2: Identification of key kinematic measures of performance and coordination for maximal undulatory underwater swimming in skilled age-group swimmers.

Aims:

(1) Examine which kinematic variables and measures of coordination provide the best predictive models for (a) end-effector cycle frequency (b) cycle length, and ultimately (c) max *U*.

(2) Establish a rationale for which measure(s) of coordination could be used as an order parameter to enable an examination of the UUS system dynamics.

Study 3: The effects of imposed cycle frequency training on the coordination and performance of skilled age-group undulatory underwater swimmers.

Aims:

(1) Compare the effects of training at a preferred cycle frequency and an imposed (preferred) cycle frequency, on the kinematics and measures of coordination of UUS in skilled age-group swimmers.

(2) Establish the efficacy of using the measured coordinative structures as an order parameter to encapsulate the USS system dynamics.

(3) Determine the efficacy of imposed cycle frequency training for promoting learning and adaptation in both the local and global UUS system dynamics.

(4) Examine the act of frequency imposition to determine its effects on performance and coordination to enable future studies delineate the effects of changing cycle frequency from the act imposition itself.

The present study will provide a foundation for future studies examining the effects of training at higher and lower imposed cycle frequencies. The findings may also inform the implementation of successful training programmes specifically designed to enable skilled athletes to progress towards optimal performance by means of a manipulation of the cycle frequency, and answer key questions regarding the process of any changes which occur as a consequence of imposed frequency training.

Chapter 2

Literature Review

2.0 Literature review

The purpose of this chapter is to review the research that has examined cycle frequencies (specifically preferred cycle frequencies) and detail its relevance to the foci of the present research. To enable a logical review of the research concerning the development, maintenance and further optimisation of a preferred cycle frequency, it is first necessary to provide a detailed outline of the dynamical systems theory (DST), which has guided much of the recent research in this area, operationally define the key concepts and terms of reference, and specify the implications of DST with regard to the present study.

To ensure a systematic and comprehensive review of the all the factors involved in the optimisation of end effector cycle frequency as a means to maximise the UUS performance in skilled swimmers, the research will be presented and discussed in terms of the coordination and control of movement, and hydrodynamic aspects of performance. To this end the review is comprised of three sections. In the first section a review of the key theoretical frameworks is undertaken to contextualise the current research. The second section addresses the motor control/learning research specifically related to the development of a preferred movement frequency. The third and final section outlines the hydrodynamic factors which influence performance of UUS, identifies the main themes of the research and presents a summary in relation to the research questions posed in the present thesis.

2.1 Literature review section one: Theoretical perspective

2.1.1 Coordination and control of movement: A theoretical perspective.

A number of definitions of coordination have been put forward. One of the most succinct was proposed by Turvey (1990), whereby coordination is viewed as '... the patterning of body and limb motions relative to the patterning of environmental objects and events...'(pg: 938). Whilst the Turvey (1990) definition is adequate to explain what coordination is, the question of how functional, goal-directed coordination is achieved is a much more complex matter altogether. To explore how this coordination is developed, achieved or indeed limited, the works of Bernstein (1967, 1996) and Von Holst (1939, 1973) must be reviewed.

Bernstein (1967) defined coordination as the problem of mastering the vast numbers of degrees of freedom (DoF) evident in the movement to be performed, namely the control of a very large number of 'multiply nested musculoskeletal subsystems' (Amazeen *et al.,* 1998). This notion has commonly come to be referred as Bernstein's (1967) 'degrees of freedom problem'. Given all the possible degrees of freedom of the human body (approx. 792 muscles; in excess of 100 mechanical degrees of freedom within all the joints; each limb being able to be described in terms of position/velocity, etc), it soon becomes evident that control of this system cannot be performed by some type of homunculus or executive control (Turvey, 1990; Thelen, 1995). This epiphany represented a major shift away from the pervasive cognitive paradigm, which had previously dominated the motor control and motor leaning research domains.

The cognitive theoretical framework explains the control and execution of coordinated movement, utilising the concepts of motor programmes (Fitts and Posner, 1967; Heuer, 1991; Schmidt and Lee, 1999) and schema theories (Pew, 1974; Schmidt, 1975). The principal tenet of this theoretical framework is that the body is centrally controlled (enslaved) by the brain/central nervous system (CNS). Motor programmes/schemas (a set of coded instructions or memorial representations of movement) are executed in response to perceptual stimuli, controlling all aspects of the effected movement response. This stimulus-response model was likened to a model of information processing commonly employed to develop and analyse computational processes. Again, this typifies the cognitive approach to human movement based on the notion of a centrally based executive control that underlies the organisation and execution of coordinated movement.

A major criticism of the cognitive perspective is that given the complexity of the system to be controlled (Bernstein's DoF problem), how can a motor programme account for and control all the possible DoF's involved in the successful execution of a movement[1]? The extent of the computational resources (space and processing speed) required is further compounded when it is understood that the coordination of a movement and the information needing to be processed operates within an environment where the internal and external conditions are constantly changing (Van Ingen Schenau *et al.,* 1995; Clark, 1995), even as a consequence of the initiation/execution of the movement prescribed by the motor programme itself.

[1] Further criticisms of this approach include arguments pertaining to how motor programmes are stored, how novel movements are produced if no motor programme is in place to describe the movement, or the argument of infinite regress (who does the programming?). However, addressing all these arguments is beyond the scope of this review.

According to Schöner and Kelso (1988), in complex systems such as those involved in multi-joint coordination, it is not possible, or even useful to determine the specific features of each DoF, further confronting the efficacy of the cognitive approach.

Von Holst (1973) recognised the need to understand coordination as a function of temporarily assembled coordinative structures with multiple underlying subsystems (Amazeen *et al.,* 1998). According to Van Emmerik *et al.* (2004) the research of Von Holst (1939, 1973) examining the coordination of the rhythmic fin movements in decerebrated fish[2] (*Labrus*) provided a major impetus for the development of this more *global* approach to an understanding of how coordination is achieved. Von Holst (1939, 1973) focused on the observation that when isolated, the individual fins of a fish each had a preferred frequency of oscillation dictated by its defining mechanical properties such as stiffness and inertia, but when swimming would oscillate at a common frequency. Von Holst (1939, 1973) distinguished two different forms of coordination which occurred between pairs (or series) of rhythmically oscillating fins, namely absolute and relative coordination.

Absolute coordination refers to a situation where the interacting (coupled) components (two or more) preserve a constant phase (e.g. phase (Φ) = 0; $\Phi = \pi$) and frequency (1:1, 2:1, 3:2, etc) relationships (Kelso, 1994). Von Holst (1939, 1973) discovered that when swimming either form of coordination could emerge and begin to dominate the coordination of the oscillating fins, yet the other form would still be present. It was postulated that the competition and/or cooperation between

[2] Von Holst also modelled this type of behaviour in mechanically coupled oscillators: see Turvey (1990) for a description.

component oscillators was the cause of the fluctuations between relative and absolute coordination (Turvey, 1990). The competition between oscillators, each having their own preferred frequency (to satisfy internal dynamics) was termed the maintenance tendency. The cooperation between component oscillators was observed as the tendency for each fin to be attracted towards the preferred frequency of the other fin(s), and was termed the magnet effect (Amazeen *et al.,* 1998). Thus, it was assumed that the preferred frequency of a system of coupled oscillators is either the preferred frequency of one of the component oscillators if that fin frequency completely dominates the other, or more likely a frequency located between the preferred frequencies of the individual component oscillators (Turvey, 1990).

Von Holst (1973) concluded that even when absolute coordination predominated, the maintenance tendency remained, and when relative coordination dominated there was evidence to suggest the magnet effect was still affecting the system. Turvey and Schmidt (1994), recognised that a system's rhythmic coordination could be analysed simultaneously in terms of the tendencies of individual component oscillators to oscillate at a preferred frequency, and the coupled oscillators 'collective' tendency to act as a single functional unit, enabling a more intuitive examination of Bernstein's (1967) DoF problem.

The complexity of the vast number of DoF to be coordinated can be resolved for a movement system as synergistic relationships between the component subsystems (Haken, 1996, 1997). These synergistic relationships serve to reduce the dimensionality of the system to be controlled, thus effectively reducing the DoF to be

controlled (Muchisky *et al.,* 1996). Turvey (1990) suggested that the problem of mastering the DoF's is reduced if a movement system is not simply viewed as the sum of its component parts but, rather as synergistic relationships apparent between key subsystems. According to Schöner and Kelso (1988), it is possible that the principles of coordination are evident in the movement patterns themselves, as fundamental patterns of coordination (i.e. transitions between quadrupedal locomotion patterns – walking → trotting → galloping) are common across a disparate range of four legged animals irrespective of anatomical structure and scale (Pennycuick, 1975; Schöner and Kelso, 1988; Turvey, 1990). Therefore, the acquisition and/or development of functional goal-directed coordination patterns can be viewed as the search for and exploitation of these functional muscle synergies which encapsulate the DoF of a system in a more manageable form (Davids *et al.,* 1999).

As previously stated, the work of Bernstein (1967) and Van Holst (1937, 1973) provided the impetus for a re-examination of the control of coordinated movement. This resulted in a 'paradigm shift' away from a cognitive theoretical framework of coordination control and towards a concept of 'self-organisation'.

2.1.2 Self organisation and dynamical systems theory: A synergistic approach.

The occurrence of 'self-organisation' of inter and intra dependent systems was a well documented phenomenon in physical and chemical systems long before any attempts were made to empirically verify its presence in a system of human movement coordination (Schöner and Kelso, 1988). The concept of self-organisation in this context implies a spontaneous pattern generation as a consequence of the interaction of a very large collection of subsystems that may adapt in response to changing internal and external conditions, by adopting coordination patterns without any explicit prescription of said pattern (Schöner and Kelso, 1988; Beek *et al.,* 1995).

Researchers (McGinnis and Newell, 1982: Turvey, 1990; Beek *et al.,* 1995) in the fields of motor control/learning and biomechanics have suggested that there is a need for an integrated approach to enrich our understanding of the acquisition and development of skilled coordinated performance. Turvey (1990) suggested that a dynamical systems framework could be such an approach. According to Kelso (1994) the concept of self-organisation expressed in the language of dynamical systems theory (DST) serves to bridge evolutionary, developmental and learning processes of coordination as it can be applied across neural, behavioural and cognitive levels of a description of coordination. Dynamical systems theory is an interdisciplinary theoretical framework used to describe and examine different types of systems (i.e. biological, computational, social, etc) that are in a constant state of flux, changing and evolving over time (Davids *et al.,* 2003; Davids *et al.,* 1999).

Self-organisation is framed by a collection of terms and constructs which in combination are used to explain the phenomena. A brief overview of these terms / constructs will be presented to clarify how self-organisation relates to the work of Bernstein and Von Holst and how it has informed the dynamical systems theoretical framework.

As previously mentioned functional goal directed coordination can be viewed as a search for and exploitation of functional muscle synergies. This *synergistic* approach to understanding the pattern formations (coordination) in human movement refers to the modelling of the observable relationships between component subsystems of a coordinative structure, without making assumptions regarding the internal properties and / or mechanisms which define these subsystems (Van Emmerik *et al.,* 2004). Proponents of the synergistic approach (Haken, 1977; Haken *et al.,* 1985; Kelso, 1995) suggested that a system's behaviour should be analysed in terms of the evolution of a collective or order parameter, with respect to perturbations caused as a consequence of the manipulation of a specific control parameter. The terms collective and order parameter have been used interchangeably in previous literature and refer to variables used to describe the 'state' of a system, identifying both the macroscopic aspects of a system and the 'collective behaviour' of the component subsystems involved (Van Emmerik *et al.,* 2004).

In previous analyses of cyclical movement tasks, the relative phase between limb movements (oscillations) have been regularly employed as an order parameter to examine the organisation of a system at a synergistic level, as phase differences

reflect the fundamental cooperation and competition evident within a movement system (Von Holst, 1939, 1973; Van Emmerik *et al.,* 2004). A control parameter is an arbitrarily selected, non-specific variable (e.g. cycle frequency, cycle velocity, inertial characteristics, etc) which can be systematically manipulated to examine the evolution of an order parameter.

According to Beek *et al.* (1989), the manifestation of a stable relative phase relationship is a defining characteristic of skilled rhythmic / cyclical performance and a critical element of a synergistic understanding of self-organisation. However, Post *et al.* (2000) demonstrated that even in highly skilled performers the relative phase relationships which describe a coordinative structure are not maintained perfectly. Turvey (1990) suggested that this 'quasi-periodicity' or variability in the relative phase is both 'inevitable and desirable'. Turvey (1990) also stated that biological systems are not characterised by exact replications or reproductions of specific patterns of motion, and that variability ought to be perceived as flexibility in the system dynamics and an essential property of that system. The concepts of stability and variability mentioned above are the key facets of an understanding of coordination at a synergistic level, as they represent the functional state of the coordinative structure. Prior to reviewing these, and other related concepts (transitions, bifurcations, etc), topological dynamics will be introduced in order to maintain a logical structure to the review.

2.1.3 Topological dynamics

Within this framework there are a number of interrelated constructs associated with the concept of the self-organisation of a movement system (Newell, 1991; Newell and McDonald, 1994). One of these constructs is topological dynamics, used to describe and analyse the system dynamics as a representation of particles or systems of particles in space (Rosenberg, 1977). This topological framework, in relation to a system of human movement is based on the assumption that only one single point of the body (joint, segment or specific point) can occupy a position in space at any given instant in time (the concept of impenetrability) (McGinnis and Newell, 1982). The concept of impenetrability asserts that motions of a number of constituent parts of a particular movement system can be represented within certain action boundaries or 'control space' (McGinnis and Newell, 1982).

Control-space, as a means of description of a particular system, can take different forms (configuration-space, event-space, state-space or state-time-space)[3] depending on the complexity of the temporal and spatial characteristics of the system to be described or analysed. The most suitable and consequentially most commonly applied control space used to analyse inter and intra limb coordination is state-space; a consequence of the complexity of the variations in the temporal and spatial characteristics of human movement. Previous research (Saltzman, 1979; Turvey *et al.,* 1978) has applied the concept of state-space to articulate Bernstein's (1967) DoF problem, demonstrating that a control space of sufficient dimensions can represent the boundaries of the interactions of a specific system. The state-space of a specific

[3] For a more detailed explanation of the various forms of control space see McGinnis and Newell, (1982).

coordinative structure is a representation of the configuration (position) of that system at a particular instant in time, relative to the velocities of the component part(s) of said system at the same instant in time (McGinnis and Newell, 1982).

The evolution of the state of a system over time is defined by the state trajectory. This notion of a state trajectory is commonly referred to in the literature as a phase-plane, and is utilised to assess stability in dynamic systems. Burgess-Limerick *et al.* (1991), elaborated further explaining that a phase-plane provides a dynamically based examination of the state of motion of a system in *n*-dimensional space, affording an opportunity to analyse the emergent features of a movement system (stability, bifurcations, transitions, etc).

A method often employed to analyse the state and evolution of system behaviour is the analysis of the system (or components of the system) in terms of their oscillations. According to Kelso (1994), the concepts of rhythm and oscillation are essential in the study of dynamic quasi-periodic evolutionary coordinative structures. The principles which underpin these complex oscillatory/cyclical systems are essentially simplistic, offering insight into how these systems evolve towards stable and functional states of coordination. According to Kelso (1994: pg. 304), rhythmic oscillations should be viewed as '...archetypes of time-dependent behaviour...' and the foundations of our understanding of system dynamics and the development of coordination.

Analyses of the structure and interactions within and of rhythmic/cyclical movement systems have been modelled repeatedly in terms of the relationships apparent within or between *self-sustained oscillators* in both mechanical and human movement systems (Hramov *et al.,* 2006; Delignieres *et al.,* 1999). An oscillatory system, in the context of human movement, refers to a system that can maintain continuous oscillation (e.g. raising and lowering the arms or flexion and extension at the wrist) for a sufficient period to satisfy any task constraints. For a system to be termed self-sustained (as in the example of the arm and wrist motions above) the primary energy source driving the motion (chemical energy stored in the muscles) must be non-oscillatory or oscillate with significantly different temporal and spatial characteristics (Turvey, 1990).

According to previous research (Haken *et al.,* 1985; Kelso, 1994; Thelen, 1995), self-organisation occurring as stable coordinative structures should be analysed as non-equilibrium dissipative systems (Kugler *et al.,* 1980), in terms of the nonlinear couplings among the component subsystems of a coordinative structure. Schöner and Kelso (1988) stated that non-equilibrium systems generally obey dissipative dynamics, explaining that, the many possible trajectories of a movement system (irrespective of the systems initial conditions) will eventually converge around a limited set of stable state trajectories (e.g. a limit cycle oscillator), otherwise referred to as an 'attractor state'. Glazier *et al.* (2003) elaborated, stating that functionally preferred, highly stable coordination or 'attractor states' evolve and develop to enable and sustain goal directed actions.

According to Beek *et al.* (1995), central to the DST approach to movement coordination and control is the identification of a system's attractor state or states, and the transitions between states as a consequence of a variation in a specific control parameter. Quantitative and qualitative analysis of the evolution of a system's behaviour in response to a perturbation, is the principle mechanism by which its behaviour can be interpreted, as it is generally impossible to derive analytical solutions of the time-dependent evolutions of a nonlinear system (Beek *et al.,* 1995).

Typically, the stability of a specific coordinative structure is assessed with respect to either a brief perturbation of the system (order parameter) by manipulation of a control parameter, or systematic increase/decrease in the magnitude of a control parameter. Key behaviours assessed are critical fluctuations and critical slowing down (relaxation time). A critical fluctuation refers to the increased variability observed in the order parameter's behaviour as it deviates away from an attractor state around a transition point (Kelso *et al.,* 1986; Schöner *et al.,* 1986). This behaviour is known as a bifurcation, a sudden nonlinear change in behaviour from stable behaviour to another more/less stable behaviour, in response to a linear increase/decrease in a control parameter. Critical slowing down or relaxation time refers to the phenomenon, whereby the time taken to return to a stable pattern of behaviour after removal of an external perturbation, can increase as a consequence of loss of stability of the attractor state (Kelso *et al.,* 1993; Scholz *et al.,* 1987). Kelso (1994) highlighted that the generic mechanisms of stability and variability are universal to all instances of phase transitions and / or pattern formations even though

they can be instantiated at various levels of movement system (Neural, energetic, hormonal, maturational, etc). It is this universality or generality of phase transitions which make the DST approach so appealing to movement scientists (Haken *et al.,* 1985). The behaviours which occur in response to these perturbations reveal important information regarding the underlying, emergent properties of a system (Kelso *et al.,* 1993), and will be discussed more thoroughly in the following sections of the review. Understanding that the act of imposing a preferred cycle frequency may in itself represent a manipulation of a control variable, the resultant effects on the order parameters needs to be determined.

As stated at the beginning of this chapter the purpose of the section was to introduce the theoretical background informing the present research. This was undertaken to expedite the following section of the review which concentrates specifically on the development and modification of preferred movement frequency in human movement.

2.2 Literature review section two: Preferred coordination.

The second section of the literature review examines research pertaining to the occurrence, maintenance and development of preferred coordination states (specifically preferred movement frequencies) and their relationship with performance optimisation. To comprehensively analyse preferred movement frequencies the literature relating to the DST and the acquisition of skilled behaviour must be explored.

Firstly, it should be recognised that the skilled performers, which form the focus of the present study, would be situated in a 'latter' phase of learning or beyond. However, it is important to first contextualise the development/learning process as it occurs from novice to skilled. An understanding of this process, as it is explained here, will provide the basis for an appreciation of any changes that occur as a result of the interventions undertaken within the present study.

2.2.1 Learning: From novice to expert.

According to Mitra *et al.* (1998) the dynamical systems approach to motor learning suggests that analysing the early phase of learning a specific movement pattern entails a search for, and the establishment of, a relevant 'collective' variable, or order parameter. As stated previously, this order parameter encapsulates the specific spatial and temporal information of the sub-systems or active degrees of freedom (ADF) that combine to produce the movement pattern(s).

The example of riding a bicycle is an excellent analogy of how this process is conducted in early learning. The novice rider is attempting to control a vast number of ADF, not only of their own body, but also its interaction with the moving parts of the bicycle. A single parameter, the balance required to remain upright on the bicycle and still continue with the cycling action can be used to encapsulate the *order* of this complex system. Mitra *et al.* (1998) proposed that this search for, and establishment of an order parameter is an attempt to minimise or simplify the movement equation to a single, or a smaller collection of variables that captures the relative variations and contributions of all the ADF to the performance of a task.

The search for a functional coordinative state is typified by the large variability in coordination apparent in the early stages of learning a novel task (Clark and Philips, 1992). The large variability associated with the early stages of learning is thought to allow a learner to explore the state-space, (all the possible states of a dynamic system) in the quest to find approximations of solutions to the movement problem(s) which are bounded/limited by the interaction of the task, environment and individual constraints (action boundaries).

The intermediate learning phase is identified as a process of stabilisation and standardisation and involves a continued effort to refine the sub-systems and manipulate the ADF in an effort to improve performance (Mitra *et al.*, 1998). The research of Nourrit *et al.* (2003) exemplifies this learning process, demonstrating the manner in which the coordinative system searches the state-space (which manifests as high variability), stabilises around particular patterns of coordination as learning

progresses (reduced variability), and then increases variability as the system further searches for ever more efficient and effective ways to perform. An increase in variability also occurs as practice of a particular task continues, and as a learner becomes more able to control, 'unfreeze', or release the ADF (Van Emmerik *et al.*, 2004). The concomitant increase in variability represents the system searching and adjusting to discover more appropriate and/or successful responses in light of the changes occurring as a consequence of this release. As practice/exposure to a task and learning continue, further standardisation occurs (reduced variability) around other stable coordination patterns, perpetuating the process.

Further to this notion of variability, Van Emmerik *et al.* (2004) suggested that the vast number of ADF which encapsulate a movement system should not be viewed as a curse, but rather a means to facilitate a more flexible control of the system (multiple states of a coordinative system can be brought into play to solve a specific task). Having an abundant number of ADF allows various combinations of these ADF to be formed into temporally available/stable synergistic task dependent coordinative structures (Kugler and Turvey, 1987; Turvey, 1990).

As acquisition of skill is characterised as a complex process, any changes in the coordination used to achieve a task should be perceived as a search for more efficient and effective solutions within the perceptual motor workspace (Newell *et al.*, 1989). Nourrit *et al.* (2000) suggested that when applying a DST framework, the understanding that the perceptual motor workspace is not static must also be taken into account. According to Nourrit *et al.* (2000) a progressive improvement in skill

leads to the incorporation of additional constraints, i.e. as the perceptual motor workspace evolves and the action boundaries are reformed with practice, the initial solutions to a motor problem enrich the set of constraints acting to re-launch the search process. Therefore, the introduction of an imposed frequency as an additional constraint may act as an impetus for further exploration of the perceptual motor workspace. The effect of the 'imposition' of this additional constraint on coordination and performance is of great interest to coaches and athlete. The implementation and success of specific strategies in provoking a search and change in coordinative behaviour for the achievement of more successful performances is the fundamental goal of both the coach and performer.

The latter phases of learning are epitomised by a continual search of the state-space for smaller and smaller adjustments in coordination around previously established movement patterns (Mitra *et al.,* 1998). This latter stage of skill acquisition is also exemplified by the exploitation of non-muscular forces such as gravity and the inter-segmental dynamics to develop and refine solutions to the movement problem (Van Emmerik *et al.,* 2004; Delignieres *et al.,* 1998). The continued evolution of these coordination patterns results in a reduction in the variability[1] around a single, or a series of stable attractor states. A number of researchers (Bootsma and Van Wieringen, 1988, 1990; Sprigings *et al.,* 1987; Franks *et al.,* 1985) have recognised that this reduced variability is one of the defining factors of skilled sports performers.

[1] While skilled performance can be characterised by low variability, low variability by itself does not characterise skilled performance. Firstly, each individual has their own characteristic, idiosyncratic performance; as such it is not a search for a generic model of an 'ideal' performance to be variable around. Secondly, highly stable coordinative structures can form which do not satisfy the task demands.

The relationship between variability and stability is important and complex and one which cannot be simply represented by increased variability equating to a reduction in stability, without an understanding of the underlying movement dynamics (Van Emmerik and Van Wegen, 2000).

Stability within the framework of DST refers not to an unyielding, stereotypic repetition of a pattern of coordination, rather the capacity of a system to quickly return to an attractor state after perturbation (Nourrit *et al.*, 2000). Thus, stability in this sense enables performers to maintain 'stable' task related coordinative structures whilst simultaneously possessing a degree of flexibility and adaptability within the system to modify behaviour as a consequence of perturbations to the system. Glazier *et al.* (2003) reiterated this point stating that the variation between multiple attractor regions enables flexible and adaptive motor system behaviour.

Schöner *et al.* (1992) have shown that there is potential for multiple attractor states to co-exist; thus enabling the movement system to switch between the relatively stable, simultaneously available states of coordination when perturbed. Zanone and Kelso (1992) highlighted that these multi-stable states occur early in learning and/or when the coordination dynamics are perturbed (either through learning or via a change in a control variable- i.e. cycle frequency) away from a previously established preferred stable state. What needs to be established is whether the act of imposing a preferred cycle frequency is sufficient to perturb the UUS system dynamics.

To understand how a movement system adapts, evolves and searches for optimal solutions to a movement problem during the latter 'expert' phase of learning, the literature referring to self-organisation and the exploitation of the system dynamics must be reviewed.

2.2.2 Self-organisation as a function of cost

According to Holt (1998) and Holt *et al.,* (1991) a principle tenet of the concept of self-organisation is the tendency to minimise a particular 'cost' function of the movement system. This cost, and its manifestation, is directly linked to the formation and evolution of a preferred movement frequency. A specific cost function originates as a consequence of the relationships between the individual, environmental and task constraints which encapsulate the system. The concept of a cost function can refer to factors such as the minimisation of the metabolic energy cost per cycle, relating to physiological aspects of efficiency.

A cost function can also refer to the minimisation of mechanical energy 'lost' from the system during the performance of cyclical activities that involve the maximisation of movement velocity. Coordination patterns and/or cycle frequencies which result in maximal energy return and exploitation of the stretch shortening cycle while sprinting, are examples of this type of cost function. Furthermore, the idiosyncratic constraints of an individual such as anthropometry, strength, physiological capacity, stage of maturation, etc, are all factors that affect the preferred cycle frequencies adopted and coordination patterns used to achieve them (Holt, 1998). The self-organisation of the movement system to find an optimal

solution based on cost function(s) and individual characteristics in relation to constraints imposed by the task and environment, has been described as an emergent phenomenon of the underlying elements of a dynamic system or process (Holt, 1998; Clark, 1995).

It is theorised that a stable preferred coordinative state evolves as a consequence of the movement system exploring the spatial and temporal boundaries imposed by the task, environment and individual constraints, and is developed to solve or provide best approximations of a solution to a 'movement equation' that represents a solution to the task undertaken (Schöner *et al.,* 1992; Mitra *et al.,* 1998). As such, research is required to examine whether the simple act of the imposition of a cycle frequency can stimulate further exploration of the spatial and temporal boundaries and produce more effective and/or efficient coordination behaviours. To achieve this research is required which imposes a cycle frequency that is matched to the individual's preferred cycle frequency, at which performance is currently optimised. This would provide an insight into the effect of 'imposing' the frequency independent of the effect of a 'change in frequency'. To date, the understanding of the act of imposition of a cycle frequency is unknown, as research has been limited to imposed frequencies higher or lower than an individuals' self selected preferred cycle frequency.

2.2.3 A preference for resonance

Some researchers (Goodman *et al.*, 2000; Turvey *et al.*, 1998; Holt, 1991) have suggested that the freely chosen preferred movement frequency of limb movements is that of the resonant frequency. The appeal of a resonant frequency lies in the associated benefits. Holt *et al.* (1995) reported that the metabolic cost of performing is optimised when the component limbs operate at resonance. Both cycle-to-cycle stability and reproducibility have been found to be enhanced when rhythmic limb motions are performed at their resonant frequency (Rosenblum and Turvey, 1998). Goodman *et al.* (2000) have also shown that movements occurring at a system's resonant frequency serve to minimise both the number of ADF and noise associated with the movement and also maximise predictability of outcome. Conversely, Hatsopoulos, (1996) reported that when movement frequencies are imposed on a system that produces movements above or below the system's resonant frequency, a decrease in stability is observed. This destabilisation is typically attributed to the resulting interactions of the neural and physical dynamics associated with the limbs involved (Hatsopoulos and Warren, 1996).

Empirical evidence of the preference for resonance has been provided by Holt *et al.* (1991). By modelling the mechanical properties of the human lower limb as an inverted pendulum of equivalent length, Holt *et al.* (1991) were able to accurately predict optimal stride frequency in walking, as that of the pendulum's resonant frequency. Similarly, Durand *et al.* (1994) found that after sufficient practice participants performing an oscillatory ski-simulation task tended to adopt movement frequencies (mean frequency 1.1 Hz) close to the modelled resonant frequency of the

system. Durand *et al.* (1994) also found that the achievement of this movement frequency served to increase efficiency. The amplitudes of the oscillation of the ski-simulator were also quantified, and were found to gradually increase with practice, suggesting the presence of a search strategy as proposed by Newell *et al.* (1989). However, both Delignieres *et al.* (1996) and Nourrit *et al.* (2000) proposed an alternative, more complex explanation existed to explain the data of Durand *et al.* (1994).

Delignieres *et al.* (1996) interpretation of the Durand *et al.* (1994) data suggested that the occurrence of the 1.1 Hz cycle frequency only appeared beyond a 30 cm amplitude threshold. Delignieres *et al.* (1996) argued that as two of the five participants were able to perform with amplitudes greater than 30 cm from the outset, and achieved cycle frequencies approximating the mean 1.1 Hz value similar to the resonant frequency, then practice and constraint (amplitude) could be thought to be acting independently. Nourrit *et al.* (2000) suggested that the progressive increases in amplitude with practice generated further constraints on the system reducing the ADF and guiding participants towards the system's resonant frequency. However, as Nourrit *et al.* (2000) noted, Durand *et al.* (1994) could not differentiate between amplitude and practice within their study, as changes in amplitude occurred as a consequence of practice. Nourrit *et al,* (2000) sought to address these issues in their related research, analysing the effects of an imposed constraint (required movement amplitudes – 15, 22.5 or 30 cm) on the variability of cycle frequency in a ski-simulator task.

Nourrit *et al.* (2000) found that irrespective of the imposed target amplitude condition, participants learnt to exploit the internal dynamics (reactive forces) of the system, reclaiming potential energy at the reversal points, improving harmonicity and movement economy. However, Nourrit *et al.* (2000) also suggested that the imposition of a required amplitude (constraint) prevented participants from developing an effective search strategy or attaining the theoretically 'optimal' resonant frequency. The variability and stability of the end-effector movement frequency was found to improve as the required amplitude increased, with the 30cm group demonstrating the greatest between-subject consistency and within-subject stability. With Delignieres *et al.* (1996) suggestion that the 30 cm amplitude acted as a threshold for the development of a movement frequency equivalent to the modelled resonant frequency of the system, Nourrit *et al.* (2000) proposed that a required amplitude limited the search for an optimal solution to the movement problem, suggesting that constraints which are too restrictive can limit the development of more effective and efficient solutions to the motor problem.

Rousanoglou and Boudolos (2006) examined the effects of the manipulations of bipedal hopping frequency on the force-time curves of the ground reaction force (GRF). They reported that participants were able to accurately attain both the imposed (higher and lower) frequencies, and the changes observed in rate of force development (RFD) represented the system's adaptations to the imposed cycle frequencies to maintain stability (Rousanoglou and Boudolos, 2006). Interestingly, Rousanoglou and Boudolos (2006) reported the presence of spring-like behaviour (single peak GRF) in the imposed higher cycle frequency data, but no such behaviour

(double peaked GRF) in the imposed lower cycle frequency data. This would suggest that the imposition of the cycle frequency was acting to 'tune' the resultant behaviour. Farley *et al.* (1991) have also shown spring-like behaviour to be present in cycle frequencies at or above the preferred cycle frequency and compromised and/or reduced at cycle frequencies lower than preferred. Conversely, Rousanoglou and Boudolos (2006) reported that in four of their eleven participants' spring-like behaviour was not evident at the preferred hopping frequency, as double peak GRF data were observed, suggesting a loss of mechanical energy as some of the stored elastic energy in the system is dissipated at some point within the pause during the double peak of the GRF.

The absence of spring-like behaviour does not correspond to the preference for a resonant frequency observed in previous cyclical studies; either suggesting that (i) preferred cycle frequency does not always correspond to a resonant frequency, or (ii) the fifteen seconds of hopping within the protocol was insufficient time to allow participants to shift into a preferred attractor state, and that the bipedal hopping task was sufficiently novel enough for these four participants and they were unable to achieve a resonant frequency as they were still searching the perceptual motor workspace throughout the experimental period. As the above research demonstrates, even in such a relatively simple task as bipedal hopping, it may not always be that a resonant frequency can be achieved or maintained as the preferred cycle frequency, even though it may still represent the most advantageous movement frequency to adopt.

Similarly, other measures or functions of cost may be more important to performance, such that the benefits of a resonant frequency are sacrificed by adopting other movement frequencies to meet the requirements of a specific task constraint. The work of Rousanoglou and Boudolos (2006), also highlighted that further exploration of the perceptual-motor workspace may be required to achieve resonance and reap the associated rewards.

In addition, Wilson *et al.* (2008) suggested that, while variability in coordination in skilled performers represents a functional capacity and flexibility to respond to perturbations; striving to minimise variability around set patterns of coordination to achieve performance goals may actually act to inhibit and constrain performance and further development. If there is no perturbation of a system away from these established, stable and relatively successful patterns of movement, then more successful coordinative states occurring at a resonant frequency may never be achieved and the exploitation of passive forces which accompany performance at resonance not realised. Therefore, it is necessary to search for and examine methods, by which, coordinative structures can be successfully perturbed to enable further exploration.

While the mathematic determination of the resonant frequency of UUS in skilled swimmers has yet to be established, and is beyond the scope of the present research, the exploration of the effects of the imposition of a cycle frequency on the inter and intra-limb coordination and subsequent UUS performance changes will help to determine the stability of the preferred coordinative attractor states. Also, the

examination of imposed frequency as a training method, will aid in the understanding of the efficacy of perturbing the movement system to search the perceptual-motor workspace, to either achieve the resonant frequency (and its associated benefits) or provide better approximations of a more optimal solution to the movement equation outside the systems resonant frequency.

2.2.4 Constraining coordination

In studies of the role of exploration and emergence of new behaviours, researchers are becoming less concerned with how a subject performs and more with how the interacting constraints relate to form stable coordinative structures or effect change (Thelen, 1995). This is not entirely true for the present study, which seeks to explore the changes in coordination that occur with the imposition of a preferred cycle frequency, and determine the effect of coordination changes on UUS performance. However, the importance of the process of the development of an 'optimal' coordinative state needs to underpin the relative importance of the UUS performance adaptations.

A similar process was adopted by Balasubramaniam and Turvey (2004) undertaking a series of experiments examining a complex, multi-segmental coordination problem (Hula-Hooping), were they investigated the effects of manipulating task constraints (amplitude and frequency) on inter-limb and intra-limb coordination. The first in this series of experiments by Balasubramaniam and Turvey (2004) was undertaken to determine the ADF, or more accurately, which and how many coordinative structures or synergies are required to understand the organisation and control of hula-hoop

performance. They found that two coordinative structures (hip-knee and hip-knee-ankle) could adequately explain the organisation and variability in the hula hoop performer system. Other studies of rhythmic activities have shown similar findings with cascade juggling (Post *et al.*, 2000) requiring three and Pedalo riding (Haken, 1996) requiring between and one and five coordinative structures (depending on skill level) to adequately represent the coordination of each of the systems.

Balasubramaniam and Turvey, (2004) having established the relevant coordinative structures, then examined their efficacy in terms of their ability to detect and discern changes in organisation, coordination and performance. This was achieved by manipulating the movement amplitude and frequency via changes in hoop size and then manipulation of movement frequency through imposed frequencies of ±10%, relative to the individual's resonant[2] frequency.

The effect of a change in hoop size demonstrated that the two previously identified coordinative structures were relevant and important predictors; discovering that the variations in their relative contributions to the control and organisation of hula hooping were directly related to the size of the hoop. It was hypothesised that the relative contributions of the two coordinative structures were related to the change in physical properties of the hula hoop (weight / diameter) and consequently the task constraints. Balasubramaniam and Turvey, (2004) suggested that the relative contributions of the two coordinative structures reflect the changing needs to meet the new task demands, namely the requirements for alterations in the vertical and horizontal components of the hula hoops trajectory. The coordination observed for

[2] Resonant frequency was defined as the participant's preferred movement frequency for the hula-hooping task.

the larger hoop was found to be more stable, and variability was found to increase as hoop size decreased.

Consistent with the findings of Goodman *et al.* (2000), Balasubramaniam and Turvey (2004) reported that inter and intra-limb coordination were least complicated (most stable and least variable) when performed at a participant's resonant/preferred frequency[3]. They also stated that the flexibility demonstrated in the two coordinative structures are relative to the imposed pattern stability requirements of the hoop-performer coupling; in that the changes witnessed in the relative contributions of the two coordinative structures reflected the necessary requirements to maintain the situation-dependent pattern stability, irrespective of the changes in task constraints (hoop size/imposed higher/lower frequencies). Therefore, an analysis of the act of imposing a preferred cycle frequency would further reveal the relative importance of the preferred cycle frequency itself, and also delineate any effects associated with the act of imposition.

2.2.5 Changes in coordination as a function of practice.

It is important to consider the process(es) by which changes and adaptations in coordination and performance occur. Newell (1991) proposed that learning is a discontinuous process, characterised by non-linear changes in motor behaviour in response to the interacting constraints on the system and the continual search of the perceptual-motor workspace. Such abrupt, non-linear changes in coordination have been demonstrated with manipulations of, and training at movement frequencies

[3] Balasubramaniam and Turvey, (2004) explain that the resonance refers not to the intrinsic properties of the joints *per se*, but to the resonance of the 'global dynamics of hula hooping'.

outside preferred movement frequencies. Patterns of inter-limb coordination have been shown to become unstable and shift towards topologically different, more stable patterns with a perturbation of, and continued practice at higher/lower movement frequencies (Kelso, 1995).

Both frequency and phase synchronisation have been shown to be characteristic elements of many bimanual coordination experiments (Delignieres *et al.,* 1998). Manipulations of coupled frequencies in inter-limb rhythmic coordination tasks have been shown to result in changes in the mean values and variability of a specified order parameter, i.e. relative phase (Turvey, 1998). The phase and frequency synchronisation manifestations in preferred coordinative structures tend towards absolute frequency locking (i.e. a 1:1 ratio) and strongly coupled reversal points of the component oscillators (Delignieres *et al.,* 1998).

Research by Swinnen *et al.* (1991) has shown that in a bimanual coordination task that required a 1:2 frequency ratio for contra-lateral limb oscillations, beginners typically adopted an absolute (1:1) synchronisation. Walter and Swinnen, (1994) suggested that this tendency to adopt an absolute frequency synchronisation, represents a systematic bias, which must[4] be overcome to achieve optimal coordinative structures that satisfy task demands. Similar observations have been made for more complex tasks. Vereijken, (1991) observed a preference for a 1:1 frequency ratio when examining the coupled oscillations of the platform of a ski-simulator and a performer's centre of mass (CM). Many studies have reported spontaneously adopted frequency and phase relationships during the initial stages of

[4] If the initial coordination patterns adopted by beginners are similar in phase and frequency to those required to achieve optimal levels of performance little or no changes in phase and/or frequency relationships are required.

learning to perform a motor task (Nourrit *et al.,* 2003; Temprado *et al.,* 1997; Zanone and Kelso, 1997, 1992; Vereijken *et al.,* 1992). According to Kelso and Schöner, (1988) the appearance of these initial spontaneous preferred coordinative structures is a consequence of the intrinsic dynamics of the system, rather than a specific intention of an individual.

The tendency for synchronisation in the reversal points of frequency-locked coupled oscillators is to adopt either an in phase (0°) or anti-phase (180°) relationship, with the movements initiating and/or terminating simultaneously (Haken *et al.,* 1985). According to Swinnen *et al.* (1996) synchronisation of reversal points can be interpreted as intermittent loci of control, were reversal points act as anchors for the organisation of the system. In contrast, asynchronous phase differences (i.e. 90°, 270°, etc) are more difficult to maintain, requiring effort and considerable practice (Zanone and Kelso, 1992). Moreover, the difficulty in maintaining these relative phase relationships is highlighted in their instability, a factor which is amplified with any perturbations to the system (i.e. change in movement frequency) (Zanone and Kelso, 1992).

Delignieres *et al.* (1998) examination of the preferred coordinative states of beginners learning a complex gymnastic (swing) task, found that beginners initial coordination patterns were both frequency locked (1:1) and in-phase (0°). In comparison, expert performers of the same task revealed more complex frequency locking (2:1) and phase relationships (either 90° or 270°), which enabled more efficient movement as performers were able to exploit the passive forces of the

system. The exploitation of gravity throughout the descendent phase of the swing to minimise force requirements to overcome the resistant work required in the ascendant phase, witnessed in the Delignieres *et al.* (1998) study is characteristic of expert performers' ability to take advantage of such passive forces (Bernstein, 1967; Sparrow 1983).

Delignieres *et al.* (1998) demonstrated that while beginners were able to improve their performance in terms of swing amplitude relative to initial levels over a ten session programme, the original phase and frequency relationships observed in the pre-test remained. The stability of the initial attractor states for both frequency and phase observed in the beginners throughout the training period revealed that the intrinsic dynamics of a movement system can be difficult to overcome (Delignieres *et al.,* 1998). Moreover, Nourrit *et al.* (2003) argued that motor learning should not be considered simply as the evolution from an initial disordered state to an ordered one, rather as a transition from an initial order to a higher, more adapted, task specific order.

It is important to understand that not only can the interactive effects of a number of constraints act to impede learning and the development of (more) successful coordination and/or performance, but also a single constraint can act as a 'rate limiter', inhibiting a change (bifurcation) away from a naïve mode of coordination toward a more task specific, higher order coordinative state (Thelen, 1986). Understanding that certain aspects of coordination (i.e. movement amplitude) can act to limit the development of the coordinative system, may explain why some

performers adopt and maximise performance of particular actions around what would appear to be sub-optimal states of coordination. Therefore, research is required to establish if the preferred frequency adopted, could itself act as a rate limiter. According to Teulier *et al.* (2006) care should be taken when modelling the extent of learning merely as the achievement of performance markers attained by skilled performers; as novices are able to achieve similar levels in certain performance markers (i.e. movement amplitude) whilst still maintaining a naïve/immature and typically novice coordination pattern. Indeed, the simple achievement of cycle frequencies and end-effector movement amplitudes in maximal UUS similar to those attained by highly skilled UUS performers, may not reflect optimal performance, as a consequence of the complexity of the whole-body coordination required to simultaneously maximise propulsion and minimised drag (see section 2.3).

Therefore, the goal of coaches and physical educators may not be to guide performers towards a to-be-acquired movement pattern, but rather facilitate a shift in coordination away from the initial attractor state and thus enable a search for an optimal solution to the task (Delignieres *et al.*, 1998).

2.2.6 Coordination: More than just an end-effector?

The human movement system can be thought of as being made up of a number of component subsystems of coupled self-sustained oscillators (Haken *et al.*, 1985). The benefit of modelling a movement system as an individual, or series of, self-sustained oscillators is that the components which define the self-sustained oscillators are analogous with a rudimentary mechanical description of the human form, and as a

consequence conform to basics nonlinear dynamic principles (Delignieres *et al.,* 1999). Turvey (1990: pg943) stated that a self-sustained oscillator can be defined by four principle components, (i) an oscillatory component represented by the elastic properties of the system (stiffness/spring) that ensure a return to a state of equilibrium, and the inertial properties which guarantees an 'overshoot', (ii) an energy source, to counter the loss of energy due to friction, (iii) a gate that allows energy to be passed to the oscillatory component in appropriate amounts and at the correct time, and (iv) a feedback component (derived from the properties of the oscillatory system) to control the actions of the gate

Research which has examined the relative importance of each of these four components to self-sustained oscillatory systems, have provided valuable insight into the behaviour of a single self-sustained oscillator with changes in nonlinear elastic/stiffness properties (Duffing, 1918) or feedback structures (Van Der Pol, 1934; Rayleigh, 1945).

Recent studies (Teulier *et al.,* 2006; Nourrit *et al.,* 2003; Delignieres *et al.,* 1999; Beek *et al.,* 1995) which have utilised the models created by Duffing, Van Der Pol and Rayleigh, to examine the evolution of end-effector behaviour from novice to skilled performance, have shown that the end-effectors of movement systems reveal a great deal about the interaction and exploitation of these constraints on the system. The aim of these self sustained models of performance is to provide a macroscopic model using the smallest number of terms which encapsulates the essential features of the cyclical tasks performed (Nourrit *et al.,* 2003). The damping functions (Van

Der Pol / Rayleigh) included in such models of coordination, relate to the regulation of the balance between energy lost and recaptured with a cycle of movement. The stiffness and elastic functions (Duffing series) of the self-sustained oscillators have been modelled with linear and/or non-linear terms.

Delignieres *et al.* (1999) proposed that for the ski-simulator task, the requirement of two non-linear terms to accurately model the platform's movements suggested a complex interaction within the subject-apparatus system. A linear Duffing term would normally be able to accurately model the movements of the apparatus. However, as the interactions between the stiffness of the springs and the performers' movements are more complex, the linear term does not accurately portray the movements observed. The benefits of these types of models of cyclical performance is that they provide a simple, sufficiently abstract order parameter which describes the behaviour and state of the system, thus enabling an effective examination of learning as it evolves over time.

While the work of Teulier *et al.* (2006), Nourrit *et al.* (2003), and Nourrit *et al.* (2000) provides valuable insight into the evolution of the coordination during the process of learning, Lee and Russo (1994) present a caveat regarding an over reliance on the modelling of end effectors to fully explicate the learning process. Simply because the trajectory of an end-effector can be modelled with reasonable accuracy, the assumption that the subsequent modelled inter and intra-limb coordination would also be physically realistic should be treated with caution (Lee and Russo, 1994). However, Delignieres *et al.* (1999) argue that the modelling of

end-effector behaviour should be seen as more than just a sophisticated 'curve-fitting' exercise, which seeks to provide perfectly fitting mathematical equations to empirically derived movement data. Delignieres *et al.* (1999) explains that this type of modelling work seeks to exploit the inherent dynamic properties (stability/variability and bifurcation behaviours) of the movement data ascertained from the 'system's' cyclical movements; stating the goal of the analysis is not to describe the cyclical movements, rather to identify the underlying attractors and dynamic behaviours.

Hong and Newell (2006a, 2006b) and Teulier and Delignieres (2007) have modelled the end-effector motions of ski simulator relative to the CM of the performer to provide more informed and detailed representations of the coordination observed. Hong and Newell (2006b) sought to examine the effects of practice on the local dynamics (inter/intra-limb coordination) and global dynamics (CM-Ski Simulator platform interactions), noting that the motor tasks traditionally employed (finger waggling/pendulum swinging) to assess coordination dynamics do not afford much opportunity for redundancy and/or adaptability; a direct consequence of trying to simplify the analysis of the system dynamics (e.g. Zanone and Kelso, 1992). Conversely, more complicated whole body tasks, involving a higher number of mechanical DoF[5] afford a much greater opportunity for redundancy, enabling a greater array of potential solutions to both global and local system dynamics. Consequently, the inherent complexities of these multi DoF systems result in the

[5] Distinctions between mechanical and dynamic DoF (Spatial-temporal) need to be made clear. Mechanical DoF are the principle tenet of Bernsteins (1967) DoF problem, the dynamical DoF refer to the spatiotemporal couplings of the body segments which reflect the dimensions of behaviour (Newell and Vaillancourt, 2001).

increased complexity of the task of the researcher in trying to establish the interactions between, and implications of, the relevant contributions at the local and global levels to the organisation of the system as a whole (Hong and Newell, 2006b; Vereijken *et al.,* 1992, 1997). This is of paramount importance when this relationship between local and global dynamics is considered at a synergistic level, as the local dynamics simultaneously regulate and are regulated by the global dynamics (Haken *et al.,* 1985; Hong and Newell, 2006b).

Research is now required that incorporates an analysis of the component system's global dynamics and empirically tests inter/intra-limb coordination changes (local coordinative subsystems that combine to produce end effector motions) to go beyond the description of possible coordinative structures predicted from modelled end-effectors to provide a more contextually specific understanding of the implications of these local and global dynamics on learning.

2.3 Literature review section three: hydrodynamics of undulatory underwater swimming

The third section of the literature presents a systematic review of the research pertaining to the performance of UUS in humans; thus synthesising the findings from both animal and human studies to provide a comprehensive portrayal of the current understanding of UUS performance.

Research examining UUS has previously been dominated by work investigating animal modes of undulatory locomotion. However, human aquatic undulatory locomotion has become a more popular research topic (Ungerechts, 1982, 1983, 1985, 1987; Sanders *et al.*, 1995; Sanders, 1998; Lyttle *et al.*, 2000; Arellano *et al.*, 2002; Zamparo *et al.*, 2002; Lyttle and Keys, 2004; Gautier *et al.*, 2004; Nicolas *et al.*, 2007; Connaboy *et al.*, 2007a, 2007b).

When compared directly to animals specifically adapted to an aquatic environment, human attempts at efficient locomotion in an aquatic environment have been described as feeble, clumsy, awkward and ineffective (Lighthill, 1969). There is obvious justification for such a criticism of human attempts at swimming based on the relatively poor levels of efficiency and maximal swimming velocities achieved. This comparatively poor performance has been attributed to the disparity in morphology apparent between specifically adapted animal species and the inadequately adapted human form. However, whilst the relative performance levels are noticeably different, the hydrodynamic mechanisms which influence and determine the UUS performance of animals specifically adapted to locomotion in an

aquatic medium are identical to those which determine the performance of human UUS. Ungerechts (1983, 1985, 1987), Sanders *et al.* (1995), Sanders (1998) and Arellano *et al.* (2002), have all shown that the hydromechanical principles used to describe and analyse animal UUS are relevant and appropriate for examining human UUS performance.

As stated, the majority of research investigating UUS has examined animal forms of locomotion; however research germane to both animal and human forms of UUS is presented to provide a comprehensive review of the information relevant to the hydrodynamics affecting UUS. With respect to the principal foci of the present research, it is essential to understand the hydrodynamic factors which influence and determine UUS performance, so that the specific effects of a imposed end-effector movement frequency on the production of maximal UUS performance can be determined.

2.3.1 Underwater undulatory swimming performance.

Sanders (2002) highlighted three global goals to consider when examining swimming technique with respect to the maximisation and/or optimisation of swimming performance: (i) minimisation of resistive impulse (at any given speed), (ii) maximisation of propulsive impulse, and (iii) restraint of physiological cost. Underwater undulatory swimming performance and swimming in general provides a very interesting topic for research as the periodic, rhythmic changes in the shape of the body not only provide the propulsive forces necessary for locomotion, but also simultaneously affect the resistance to forward motion, known as active drag (AD)

(Ungerechts, 1984). Therefore, to provide a comprehensive understanding of the production of maximal UUS velocity it is necessary to analyse those factors (and their interactions) which simultaneously determine the shape (frequency, amplitude, temporal couplings) and velocity of the propulsive waveform, and the AD experienced in UUS (Lighthill, 1975; Videler, 1993; McHenry *et al.*, 1995).

The identity, functions, and relationships apparent between the principal factors involved in the production of a propulsive impulse have been the focus of a vast amount of research examining undulatory locomotion in a variety of aquatic species (Gray, 1933; Webb, 1971; Batty, 1981; Fish, 1984; Fish *et al.*, 1988; Jordan, 1992; Fish, 1993; Gillis, 1997; and many others). Undulatory locomotion in all of these disparate species, is accomplished via temporally sequenced oscillations that pass along the length, or a section of a swimming body. These oscillations are such that they create bends in the swimming body that pass caudally along its length, generating an undulatory wave which transfers momentum to the surrounding fluid resulting in a propulsive impulse (McHenry *et al.*, 1995). For forward motion to occur the propulsive wave velocity must exceed the forward swimming velocity of the body. An understanding of the temporal sequencing / coupling between these oscillations as they occur along the body is fundamental to an appreciation of how UUS performance is optimised, as the composition of these oscillations and their relationships determine the shape and velocity of the propulsive waveform.

Previous research (Lighthill, 1975; Videler, 1993) has recognised that it is the shape and velocity of the propulsive waveform which determines the overall UUS velocity.

Therefore, it is essential to identify the component variables and their interactions which influence these oscillations and subsequently determine the shape and speed of this propulsive waveform. Of all the variables which influence and determine forward swimming velocity in UUS performance in marine animals, the frequency and amplitude of the end-effector, and the length of the swimming body have been the most extensively researched (Hunter and Zweifel, 1971).

The wavelength of the propulsive waveform, the style of UUS adopted and the morphology of the swimming body have also been identified as important factors in the production of an effective and efficient UUS performance. Understanding the relationships between each of these variables and how they alter with fluctuations in end-effector movement frequency and forward swimming velocity is essential to fully comprehend the mechanisms involved in the process of optimising UUS performance (Hunter and Zweifel, 1971; Bainbridge, 1958).

2.3.2 End-effector movement frequency.

Given the emphasis on movement frequency in previous sections of this review, this sub-section will concentrate on research that directly examines the role(s) and implications of movement frequency effects in UUS performance.

Of all the factors associated with the performance of UUS in marine animals, the end-effector (tail-beat) frequency has been the most studied kinematic variable (Webb *et al.*, 1984). Numerous studies (Bainbridge, 1958; Hunter and Zweifel, 1971; Fish, 1984; Long *et al.*, 1994) have consistently shown the relationship between the

end-effector frequency and forward swimming velocity to be a linear one, irrespective of the size of the animal studied or the style of UUS adopted. Webb *et al.* (1984) maintain that in all the aquatic species previously studied the relationship between tail-beat frequency and forward swimming velocity has been found to be linear, such that, as end-effector frequency increases there is a concomitant increase in forward swimming velocity.

While this relationship between end-effector movement frequency and forward swimming velocity for aquatic animals has been extensively studied, it is not via the direct (voluntary) modulation of the end-effector frequency; rather, these relationships have been determined from simple observations of the frequencies corresponding to forward swimming velocity. Therefore, any previous research which has modelled the relationship between end-effector frequency and forward swimming velocity as a linear relationship has provided an incomplete account, as the relationships reported would only represent the values of forward swimming velocity observed. Consequently, the study of human forms of UUS performance represents an excellent opportunity to investigate and determine the effects of a direct manipulation of end-effector frequency on the kinematic and performance of UUS. As human undulatory swimmers can be instructed to actively achieve and attain set frequencies whilst still trying to attain maximal forward swimming velocity, this would enable the relationships between end-effector frequency, propulsive wave velocity and forward swimming velocity to be systematically analysed. Furthermore, this would facilitate a direct examination of the effects of

changes in end-effector frequency on the other important hydrodynamic and kinematic variables involved in UUS performance.

Insufficient research has been undertaken to directly examine the impact of changes in end-effector frequency in a human form of UUS. End-effector frequency and its role in human forms of undulatory swimming have been reported (Barthels and Adrian, 1971; Arellano *et al.*, 2002; Zamparo *et al.*, 2002; Sanders *et al.*, *1995*; Sanders *et al.*, 1998; Nicolas *et al.*, 2007), but it is rarely the main focus of the research. Barthels and Adrian (1971) examined moderate and sprint performance for both the dolphin kick and full butterfly stroke when swimming at the surface. They reported that end-effector frequency was the most influential kinematic variable in terms of its influence on the forward swimming velocity compared to the changes in joint amplitudes required to perform the kicking motions, irrespective of which of the four undulatory swimming conditions was performed. However, minimal empirical evidence was presented within the Barthels and Adrian (1971) study to support this assertion.

Similar to the previous animal studies, end-effector frequency has primarily been analysed in terms of its relationship to changes in forward swimming velocity. A principal exception to this is the work of Lyttle and Keys (2004), which examined the interactions between kick frequency and kick amplitude as a means to further understand and optimise UUS performance. Lyttle and Keys (2004) used computational fluid dynamics (CFD) to model UUS performance, examining both (i) large amplitude (0.54 m) / slow (2.27 Hz) kicks, and (ii) small amplitude (0.42 m) /

fast (2.63 Hz) kicks, over a range of swimming velocities (1.50, 2.18 and 2.40 $m.s^{-1}$); with kinematics derived from a single (elite) male swimmer.

The initial CFD work of Lyttle and Keys (2004) has generated valid and reliable values for the key kinematic parameters associated with UUS that are generally in agreement with empirically derived UUS data of Arellano *et al.* (2002) (see table 2.1). Disparities between the reported values of forward swimming velocity can be explained as a consequence of the difference in the skill levels of the subjects' observed. The video data used by Lyttle and Keys (2004) were collected from a single elite male swimmer, whereas the international level swimmers data in the Arellano *et al.* (2002) study contained both male and female swimmers. Therefore, the mean values of forward swimming velocity reported by Arellano *et al.* (2002) would be directly affected by any significant differences in the mean values of forward swimming velocity achieved between male and female swimmers. Lyttle and Keys (2004) suggested that the larger amplitude/lower frequency kick was the most efficient of the two styles of kick analysed, but warn that these results may not be generalisable across the full range of possible kicking patterns utilised by swimmers.

Table 2.1 Kinematic characteristics of undulatory swimming performance

Authors & Subject Details	Subjects/Conditions	*U* (m.s.$^{-1}$)	*f* (Hz)	A (m)	*V* (m.s.$^{-1}$)
Arellano *et al.* (2002)					
Thirty-two skilled swimmers	International (n=19)	1.61	2.14	0.62	†
	National Age-group (n=13)	1.15	1.76	0.62	
Lyttle and Keys (2004)					
CFD Analysis of one elite swimmer	Large Amp/Slow Kick	2.16	2.27	0.54	†
	Small Amp/Fast Kick	2.13	2.63	0.42	
Zamparo *et al.* (2002)					
Seven collegiate swimmers	Barefoot Flutter Kick	0.6	1.29 ± 0.14	0.34 ± 0.08	†
Maximal Flutter kicking		0.7	1.44 ± 0.05	0.33 ± 0.04	
Amplitude is calculated as the		0.8	1.58 ± 0.22	0.34 ± 0.04	
maximal distance between the		0.9	1.73 ± 0.15	0.37 ± 0.03	
ankles in flutter kicking.		1.0	1.90 ± 0.07	0.36 ± 0.04	
	Fin Flutter Kick	0.7	0.73 ± 0.14	0.30 ± 0.04	†
		0.8	0.92 ± 0.17	0.30 ± 0.07	
		0.9	0.98 ± 0.20	0.31 ± 0.06	
		1.0	1.18 ± 0.15	0.29 ± 0.05	
		1.1	1.29 ± 0.16	0.33 ± 0.05	
Connaboy *et al.* (2007a)					
Fifteen collegiate swimmers	Maximal UUS	1.24 ± 0.47	2.11 ± 0.03	62.9 ± 4.21	3.86 ± 1.25
Guillaume *et al.* (2007)	Fin UUS	2.50 ± 0.10	2.09 ± 0.31	0.55 ± 0.10	4.38 ± 0.46
Twelve French National team Mono-fin Swimmers					
Barthels and Adrian (1971)					
Four Collegiate swimmers.	Moderate Kick	0.93 ± 0.03	†	†	†
Swimming at surface with kick board	Sprint Kick	1.20 ± 0.04			

Mean values ± standard deviations reported for Average swimming velocity (*U*), end-effector frequency (*f*), end-effector amplitude (A) and propulsive wave velocity (*V*). † -Values not reported. **values calculated from mean values of height (m) reported

2.3.3 Movement amplitude.

The amplitude(s) of UUS motions have been analysed in two distinct ways (i) the amplitude of the end-effector (tail/feet) and (ii) the amplitude of oscillations of key anatomical landmarks along the length of the swimming body. The amplitude of the end-effector or as it is more commonly referred to in the marine animal research

literature, the tail-beat amplitude, is a key kinematic variable used in the determination of the effectiveness and efficiency of UUS. The amplitudes of key anatomical landmarks, along with the wavelength of the propulsive waveform, can be used to identify the type or style of UUS adopted, and have a significant influence on the AD experience by the swimming body.

Jordan (1992) noted that if tail-beat amplitude is increased and all other kinematic variables remained constant, propulsive thrust would increase. However, if tail-beat amplitude is increased the other kinematic variables of the propulsive waveform are shown to alter accordingly. The physical constraint of trying to achieve larger amplitude movements whilst trying to maintain end-effector movement frequency is restricted by the ability to propel the caudal aspects of the swimming body through greater amplitudes in the same amount of time. Additionally, both Lighthill (1971) and Webb *et al.* (1984) considered the question of the higher levels of drag associated with an increase in tail-beat amplitude, stating that both profile and frictional drag would amplify as the cross-sectional area perpendicular to the flow is increased and boundary layer flow conditions alter. In contrast, the more recent research of Taneda (1978) and Barret *et al.* (1999) have reported that large amplitude oscillations may have a part to play in efficient UUS performance, as the interaction of the amplitude(s) of the anterior aspects of the swimming body with the tail-beat amplitude can actively reduce drag (see section on vorticity control).

Analyses of the relationships between tail-beat amplitude and forward swimming velocity (Webb *et al.*, 1984; Webb, 1992) have not reported a consistent relationship. Bainbridge (1958), Hunter and Zweifel (1971) and Webb (1975), have all reported that in the UUS of fusiform (wide middle section and tapered at both ends) fish an increase in tail-beat amplitude is found with increases in tail beat frequency up to a relative value (relative to body length) of forward swimming velocity, after which tail-beat amplitude remains at a constant value regardless of changes in forward swimming velocity or tail-beat frequency. Empirical research has reported consistent relative tail-beat amplitude values of between 0.16 and 0.34 body-lengths (Fierstine and Walters, 1968; Wardle *et al.*, 1989) depending on which species of marine animal studied. Hunter and Zweifel (1971), Hertel (1966) and Blake (1983), have all suggested that irrespective of the scale of the undulatory underwater swimmer the tail-beat amplitude are approximately 0.21 body-lengths when swimming steadily.

Ungerechts *et al.* (1998) observed that the tail-beat amplitude of dolphins did not exceed a value of 0.25 body-lengths, even when increasing forward swimming velocity. This evidence suggests that tail-beat amplitude and forward swimming velocity are independent, and that an optimal tail-beat amplitude may exist for an individual undulatory underwater swimmer, were the balance between the interacting hydrodynamic constraints is optimised i.e. (i) cross-sectional area perpendicular to the oncoming flow, (ii) increased thrust from larger tail-beat amplitude, and (iii) coordination of body and tail amplitudes.

Webb *et al.* (1984) established that for rainbow trout tail-beat amplitude was significantly related to body length but not forward swimming velocity. Webb *et al.* (1984) also found that absolute amplitude increased with body-length, but when normalised to body-length, the relative amplitude decreased as body-length increased. Webb *et al.* (1984) proffered no rationale for this phenomenon. However, it would be reasonable to assume that as the length of the involved body increases, the inertia of the water to be moved as well as the inertia of the body itself increase rapidly relative to the increase in force and moment arm of the muscles. Therefore, for a comparatively longer bodied swimmer to maintain or increase tail-beat frequency relative to a shorter bodied equivalent, tail-beat amplitude must be reduced.

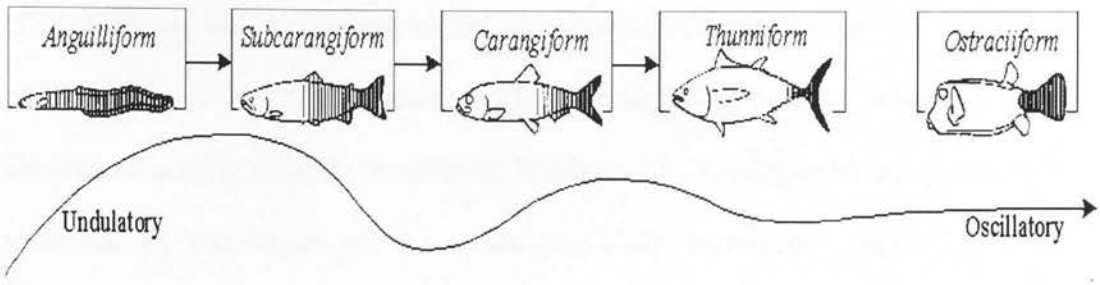
2.3.4 Wavelength, morphology and mode of undulatory underwater swimming.

It has been argued that the wavelength of the propulsive waveform occurring along the length of the undulatory swimmer is one of the most important kinematic variables when analysing UUS performance (Dewar and Graham, 1994). According to Dewar and Graham (1994) the justification for wavelength being such a significant factor in the analysis of UUS performance is threefold: (i) it defines the mode of UUS adopted, (ii) it indicates factors associated with both increases and decreases in thrust and drag, and (iii) it defines the limit of the distance travelled per kick cycle.

Propulsive wavelength has been analysed previously in two distinct forms, (i) the wavelength of the propulsive waveform over the entire length of the undulatory swimmer, or (ii) the wavelength of the propulsive waveform from one key anatomical landmark to the next key anatomical landmark. Analysing wavelength over the entire length of the undulatory swimmers is the most commonly reported measure. However, Batty (1981) argued that as propulsive wave velocity can vary along the length of an undulatory swimming body then wavelength can also vary. This potential variation in wavelength along the length of the undulatory swimming body puts into question the efficacy and validity of using an average wavelength (over the entire body length) to describe and analyse the propulsive waveform present.

Using both experimental and theoretical research Gray and Hancock, (1955), Lighthill, (1960; 1969), Webb and Weihs (1986) and Muller *et al.* (2000) have demonstrated that undulatory locomotion is an appropriate and viable method of aquatic propulsion over a range of flow regimes / Reynolds numbers (R_E). Lighthill (1969) identified that undulatory locomotion is largely insensitive to changes in scale, thus enabling UUS to function effectively over the aforementioned large range of R_E values. Nevertheless, UUS in aquatic animals occurs in many forms or modes (Figure 2.1). These different modes of UUS occur primarily as a consequence of interspecies morphological differences and variations in the requirements of migratory, predatory and/or avoidance behaviours. The fundamental characteristics of animal undulatory swimming (wavelength, body amplitudes, tail-beat amplitude / frequency, etc) have been used to classify the various modes (Table 2.2).

Figure 2.1 Modes of undulatory swimming



(Sfakiotakis et al. 1999: pg 241)

Figure 2.1 shows the changes in the form of undulatory locomotion from *anguilliform*, where undulations are present along the entire length of the swimming body (represented by shaded area), through to *thunniform* and *ostraciiform*, where the undulations are confined to the posterior sections of the swimming body.

Table 2.2 Characteristics of the various modes of undulatory locomotion.

Undulatory Swimming Mode	Fundamental Characteristics
Anguilliform	• Purely undulatory, the entire body participates in the waveform. • Short wavelength - 1 or more wavelengths per body length. • Amplitude of the body movements are relatively large along the entire length of the body • E.G. Tadpole, Eel
Sub-Carangiform	• Similar to *anguilliform*, with the exception that posterior aspects of the body are emphasised in the production of propulsive impulse. • Between ½ and 1 wavelength per body length. • E.G. Trout
Carangiform	• Only the posterior sections (final third) of the body oscillate. • Less than ½ a wavelength per body length • Minimal oscillations occur in the anterior aspects of the body. • E.G. Salmon
Thunniform	• Long propulsive wavelength • Majority of propulsive force generated in extreme caudal regions • Minimal oscillations occur in the anterior aspects of the body. • E.G. Tuna

Dewar and Graham (1994) proposed that wavelength is regulated by the mode of UUS adopted, and the morphological characteristics/constraints of the swimming body. Webb *et al.* (1984) found no significant relationship between wavelength and forward swimming velocity. In addition, Webb *et al.* (1984) reported that wavelength increased as the length of the swimming body increased. However, when wavelength was normalised to body length wavelength decreased as the length of the swimming body increased (Webb *et al.*, 1984). These findings are contrary to those of Dewar and Graham (1994) who found longer relative values of wavelength in the fastest and some of the largest aquatic species.

Although the highest relative values of wavelength are found in the fastest swimmers, wavelength alone cannot be used to analyse the effectiveness and efficiency of UUS performance. Dewar and Graham (1994) contended that even though an increase in wavelength would directly increase cycle length, there would be adverse consequences of swimming with less than one wave length per body length. In undulatory swimmers where there is less than one wavelength per body length (carangiform / thunniform) inertial recoil of the anterior sections of the body can occur as a consequence of the large amplitude movements of the tail (Lighthill, 1970). This inertial recoil can be detrimental to the production of the propulsive impulse and can increase profile drag. The propulsive impulse is negatively affected as a consequence of interference with the temporal coordination of the propulsive waveform and the profile drag is increased due to increase in cross-sectional area relative to the oncoming flow.

Sfakiotakis *et al.* (1999) stated that in an UUS mode where there is more than one wavelength per body length (a low wavelength value), such as anguilliform, the dorso-ventral forces which occur along the length of the body are cancelled-out or balanced. The presence of more than one wavelength on the swimming body acts to minimise inertial recoil. However, Dewar and Graham (1994) asserted that the anterior sections of the swimming body are ineffective in the production of a propulsive force, with more effective and efficient thrust produced by the undulations in the latter portions of the body.

To overcome the negative effects of a longer wavelength the fast swimming marine animals that adopt carangiform or thunniform modes of undulatory locomotion have appendages such as large anterior fins (pectoral or dorsal) which act to reduce the heaving (vertical) or yawing (lateral) motions (depending orientation of undulation) in the anterior sections of the body produced as a consequence of inertial recoil from the relatively large movements of the tail (Webb, 1992).

Research by Connaboy *et al.* (2007a) examining human UUS performance has suggested that skilled swimmers may use the outstretched arms in a similar manner to the pectoral or dorsal fins of carangiform swimming animals. The arms act to minimise the amplitude of the inertial recoil of the anterior sections of the swimming body thereby minimising profile drag, and providing a stable platform from which an effective undulation can be initiated. According to Lighthill, (1971) and Webb, (1992) this mechanism can enable a more effective transmission of a propulsive waveform along the caudal aspects of the swimming body. Connaboy *et al.* (2007a)

and Zamparo *et al.* (2002) have both suggested that human UUS is more like the *sub-carangiform* aquatic locomotion of trout, rather than the *anguilliform* locomotion of eels.

The morphology of an UUS animal has consistently been shown to influence the mode of UUS adopted and the effectiveness and efficiency with which UUS is performed (Schlicting, 1968; Lighthill, 1970; Chopra, 1976; Fish and Hui, 1991). The diversity in morphology in undulatory swimmers is large but certain key factors reappear constantly. Wu (1971) observed that a typical fish-like shape is characterised by slenderness across the width and transverse height of the body in comparison to its length, resembling a fusiform structure.

Previous research (Walters, 1962; Webb, 1975; Fish and Hui, 1991) has indicated that a fusiform streamlined shape reduces viscous/pressure drag by maintaining laminar flow over a greater length of the swimming body. The widest sections of the swimming body and/or the greatest changes in direction along the contours of the body are important for determining the efficiency of the shape of the swimming body. It is at these two points that boundary layer separation and the transition from laminar to turbulent flow is likely to occur. The preservation of laminar flow over a fusiform shape can only partly account for the differences in efficiency between undulatory swimmers with such diverse and distinct morphology (Fish and Hui, 1991).

According to Schlicting (1968), the thickness of the boundary layer adjacent to the swimming body expands approximately with the square of the distance from the leading edge of the swimming body. Thus, Webb (1992) suggested that, as the local drag coefficient decreases with the distance from the leading edge on a streamlined body, then the average drag experienced by a longer body is less than that of a shorter body with equal wetted surface area. Hence, a longer swimmer would have an advantage over a shorter one as a consequence of the relative reduction in drag.

The shape adopted by the body with arms outstretched in front of the swimmer when UUS acts to increase the length of the swimming body and present a more streamlined shape, effectively reducing AD (Vorontsov and Rumyantsev, 2000). Furthermore, the outstretched arms may also be acting in a similar manner to the 'sword' of a swordfish. According to Bushnell and Moore (1991), in some fast swimming aquatic species, anterior sections of the body (i.e. the sword of the swordfish) are structured so that they induce turbulent flow along the remainder of the swimming body. As profile drag has the greatest potential to retard swimming efficiency, any mechanism which can reduce its effects enhances performance.

The magnitude of profile drag experienced by a UUS body increases rapidly once flow separation occurs. By inducing minor turbulent flow (turbulent wall flow) along the anterior portions of the body (sword/arms) boundary layer separation is delayed as 'dynamic eddying motions' are created. These dynamic eddying motions can cause momentum transfer along the body, ultimately delaying the separation of the

flow, reducing the size of the wake, and minimising AD (see Bushnell and Moore (1991), for a more detailed description).

2.3.5 Hydrodynamics, flow and vorticity control.

Having reviewed the key component kinematic and structural variables (frequency, amplitude, wavelength, morphology) which combine to form and influence UUS mode and performance, it is now essential to examine how their interactions maximise the propulsive impulse and minimise the resistive impulse, whilst also optimising physiological cost (Sanders, 2002).

A possible explanation for the discrepancies observed in the performance of undulatory underwater swimmers, is the ability to control the vortices produced when UUS. When UUS is performed the heaving and pitching motions of the undulating body and end-effector can create rotating masses of water known as vortices (Arellano *et al.*, 2000; Ungerechts *et al.*, 1998; Triantafyllou *et al.*, 2000). The pitching motions are the changes in the angle of the end-effector (tail/feet) relative to the path of the swimmer. The hydrodynamics and mechanisms of the interactions between the body motions and the surrounding fluid motions (flow), has been extensively researched (Tokomaru and Dimotakis, 1991; Cortelezzi, 1996; Koimountsakos, 1999; Triantafyllou *et al.*, 2002). Triantafyllou *et al.* (2000) stated that the interactions between an undulating body and the unsteady surrounding flow are the fundamental mechanisms by which UUS performance is enhanced. The UUS performance is manipulated by means of vorticity control.

Empirical research examining animal UUS efficiency mechanisms found that series of vortices appeared along the sides of fishes and dolphins (Rosen, 1959, 1961, 1963). More recently, Muller *et al.* (1997), Drucker and Lauder, (1999; 2001), Wolfgang, (1999) and Arellano *et al.* (2002), have all demonstrated that the vortices shed from the caudal aspects of the body (tail/fins or in the case of humans - feet) produce regular patterns in the resultant flow structures. In UUS the body undulations generate a 'bodywake' and the oscillations of the caudal aspects (tail/feet) of the swimming body generate their own wake. The ability to minimise the energy lost to the bodywake and the capacity to recapture and reuse any energy transferred to these rotating masses of water via the effective control of the end-effector is thought to help determine the effectiveness of the UUS performed.

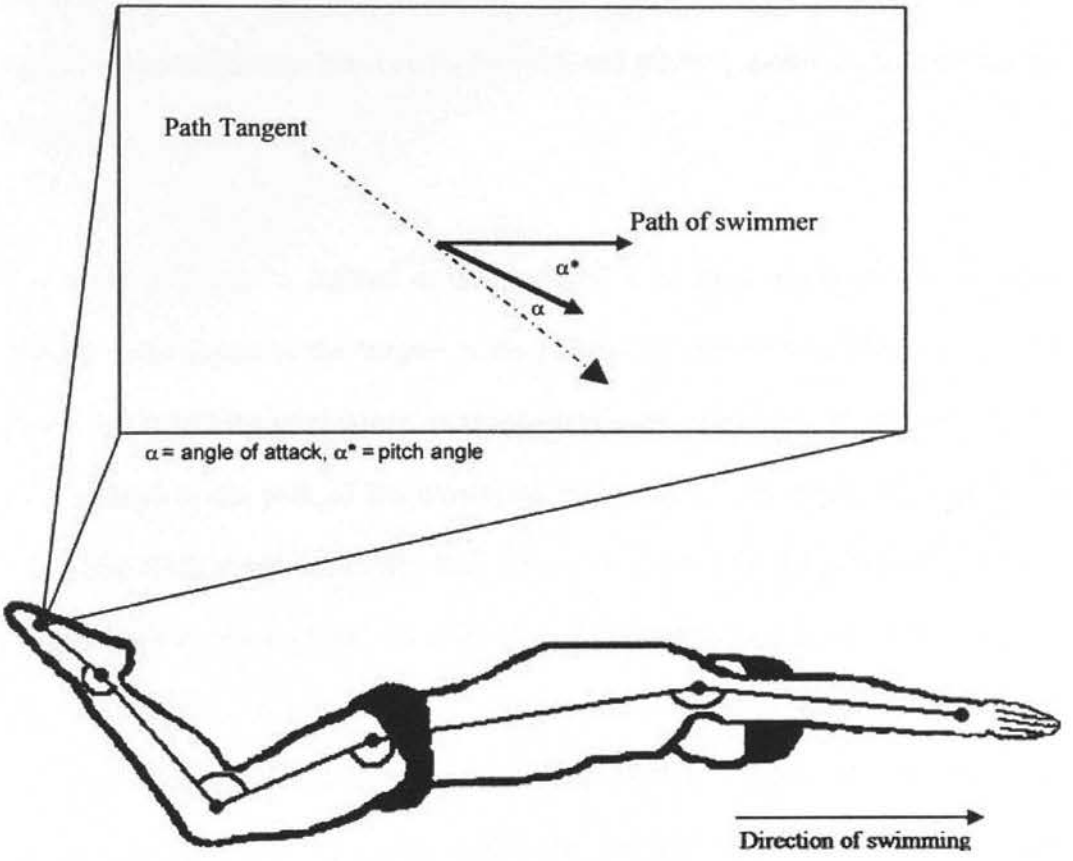
Uncontrolled flow separations in the form of vortices generated along the UUS body produce large pressure differentials, acting to reduce forward swimming velocity and decrease efficiency. An understanding of the controlling mechanism which determines the shedding of vortices into the wake is vital to comprehend how UUS bodies achieve maximal swimming velocities (Triantafyllou *et al.*, 2002). The oscillations which produce the propulsive impulse must also be sequenced, such that they minimise AD at a given swimming velocity. Triantafyllou *et al.* (2002) suggested that the relatively large amplitude oscillations which occur in UUS must also serve to control the flow over the swimming body, otherwise these undulatory motions could lead to flow separation and the generation of vortices, increasing AD and degrading UUS performance.

Barret *et al.* (1999) stated that the propulsive impulse required to propel an active UUS body is considerably less than the impulse required to tow the same body in a rigid position at an identical swimming velocity. Rosen (1961, 1963) theorised that properly sequenced undulatory body motions synchronised with the vortex flow over the body could facilitate the recovery of some of the rotational energy contained within these vortices, thus improving propulsion. Theoretical and experimental research (Webb, 1975; Triantafyllou *et al.*, 1991, 1993; Fish 1993) examining UUS in cetaceans (marine mammals – dolphins, whales, porpoises) proposed that the tails/flukes act as hydrofoils which heave and pitch in an oscillatory manner. The performance of oscillatory hydrofoils is known to optimise within specific ranges of pitch angle and angle of attack (Anderson *et al.,* 1998). Therefore, the observed behaviours of the pitch angle, angle of attack and the phase relationship between heaving movement and pitch angles can be compared against values calculated from empirical research.

The oscillatory heaving and pitching motions of the end-effectors in UUS act to alter the angle (pitch angle) between the end-effector and the path of the swimmer (Figure 2.2). The heaving motions are the vertical, quasi-sinusoidal motions produced at the end-effectors (caudal peduncle/ankle joint) during UUS. A pitch angle of zero signifies that the axis of the end-effector is parallel to the path of progression of the swimmer, effectively minimising drag encountered by the end-effector, although negating the generation of an effective propulsive impulse (Fish and Rohr, 1999).

Anderson *et al.* (1998) remarked that the phase relationship between the heaving and pitching motions is critical to the production of an effective propulsive force and the simultaneous minimisation of AD, as it determines the formation and the timing of the shedding of the vortices from the leading edge of the end-effector.

Figure 2.2 Pitch angle and angle of attack in UUS.



Anderson *et al.* (1998) suggested that within aquatic animals which satisfy a specific relationship between the length of the end-effector (c) and the rotational axis of the pitching movements along that end-effector (d)

$$d = \frac{2}{3}c \tag{1}$$

a phase angle difference of approximately 75° (pitch leading heave) represents the optimal phase difference between the heaving and pitching motions (Anderson *et al.*, 1998).

The angle of attack is defined as the angle of orientation of the axis of the end-effector with respect to the tangent of the path of the end-effector (Figure 2.2). The ability to control the pitch angle by manipulating the orientation of the end-effector with respect to the path of the swimming body enables the angle of attack to be controlled (Fish and Rohr, 1999). According to Webb (1975) the generation of thrust (in lift based swimming) and the efficiency of propulsion are greatly affected by the angle of attack of the end-effector. Increasing the angle of attack of a hydrofoil would increase both lift and drag, with lift increasing at a higher rate than drag. The increase in both lift and drag observed would continue until a critical level of angle of attack, beyond which, further increases in angle of attack will result in higher levels of drag and an abrupt decrease in lift (Fish and Rohr, 1999).

Research examining human hydrofoils for aquatic propulsion (Wood, 1979; Berger *et al.* 1995; Marinho *et al.*, 2009; Bixler and Reiwald, 2002) has concentrated on the path and orientation of the hands and arm within the different swimming strokes.

These studies have examined the implications of the hand/arm complex as an hydrofoil under quasi-static conditions i.e. with models of the limbs placed in a flow of air or water and the component lift and drag forces measured with changes in angle of attack, pitch angle and/or sweepback angle. However, as Toussaint et al. (2000) suggested, the efficacy of this quasi-static approach may be questionable, given the constantly changing path and orientation of the hand and arm throughout the swimming strokes. Toussaint et al. (2000) noted that the characteristics of *unsteady flow* may be more appropriate in examining how effective and efficient aquatic propulsion is achieved.

The maximal angles of attack observed in oscillatory hydrofoils are considerably higher than those achieved in non-oscillatory or stationary hydrofoils. According, to Maresca *et al.* (1979), oscillatory hydrofoils perform more efficiently at higher angle of attack compared to stationary hydrofoils. Fish and Rohr (1999) stated that conventional stationary hydrofoils in steady flow conditions stall at approximately 15°. In comparison, values in excess of 30° have been achieved for oscillating hydrofoils (Triantafyllou and Triantafyllou, 1995).

The difference in values at which stall occurs between the stationary and oscillatory conditions can be explained by the concept of dynamic stall (Anderson *et al.*, 1998; Maresca *et al.*, 1979). The oscillatory motions act to delay the separation associated with stall, increasing lift via the formation of a leading edge vortex (Ellington, 1995; Triantafyllou, *et al.*, 1996; Anderson *et al.*, 1998). According to Fish and Rohr (1999), the formation of a leading edge vortex enhances the difference in flow

velocities above and below the foil, resulting in a greater pressure differential between the two surfaces and a concomitant increase in both lift and thrust. Thus, measures of angle of attack and pitch angle can provide further insight into how effectively a swimmer recaptures energy from the bodywake and manipulates the profile drag and propulsive impulse to effectively control the vortices shed into the wake (discussed later in this section).

The preservation of a positive angle of attack within a specific range (between 15° and 25°) has been shown to provide optimal levels of thrust production throughout the undulatory cycle for a variety of aquatic species of animal (Sfakiotakis *et al.*, 1999; Videler and Kamermans, 1985; Triantafyllou *et al.*, 1993). When analysing the effectiveness of thrust production over a range of swimming velocities, the observed values of angle of attack have been reported to range from 4.6° to 30° for a variety of aquatic species (Fish, 1993; Lang and Daybell, 1963). Chopra, (1976) suggested that an angle of attack of 30° may represent the upper limit for oscillatory systems, with values above 30° resulting in a reduction in both thrust and efficiency. There has yet to be any empirical evidence reported to show the magnitude of the values achieved for the angle of attack of the end-effector, or indeed, the efficacy of end-effector angle of attack as a measure of the performance in human UUS.

If the caudal aspects of the swimming body are considered to act as a hydrofoil then it is possible to model their behaviour as waving plates in oncoming steady flow (Triantafyllou *et al.*, 2002). The research of Hertel (1966) and Anderson *et al.* (1998) which modelled the motions of the tails of UUS animals as waving plates,

proposed that the phase relationships between the heave and pitch oscillations act to determine and control the propulsive performance of the caudal aspects of the swimming body. Taneda (1977) demonstrated that a single oscillating flat plate placed in oncoming steady flow conditions would function to reduce turbulence and flow separation when the phase speed of the oscillations of the plate approached comparable values of oncoming flow velocity. Anderson *et al.* (1998) stated that the oscillatory heaving and pitching motions of a hydrofoil in an oncoming flow result in unsteady shedding of vortices from the trailing edge. The production of these unsteady, intermittent vortices from the trailing edge generates jet flows and given the right conditions these jet flows can produce additional thrust to overcome the AD (Triantafyllou *et al.,* 2002). Significant drag reduction mechanisms have also been demonstrated by both Taneda (1978) and Tokomaru and Dimotakis (1991) for oscillating cylinders (when compared to the same cylinders in static condition in identical flow conditions), with the width of the wake behind the oscillating cylinder being reduced as a consequence of the oscillations, effectively reducing AD.

Computational analysis of a flat plate undergoing a travelling wave oscillation in a steady flow, has shown that as the speed of the travelling wave phase oscillations approached the value of the oncoming flow velocity, separation and vortex production decreased (Zhang, 2001). Techet (2001) and Zhang (2001) have both demonstrated that the energy required to tow and oscillate a waving plate was minimised when the value of flow velocity / wave phase velocity reached a value of 1.2. This confirms observations found in live UUS fish, where preferred values of

flow velocity / wave phase velocity of 1.2 have been recorded (Triantafyllou *et al.*, 2002).

Given the formation of wakes both on the body and at the tail, Muller *et al.* (2002) suggested that swimming motions of UUS swimming fish can be represented by the actions of two waving plates, with one plate positioned in the wake of the preceding plate. The first (upstream) waving plate represents the undulations of the swimming body, the second the actions of the tail. Muller *et al.* (2002) suggested that it is the interaction of the 2nd waving plate (the tail) with the vortices generated by the 1st plate (the body wake) which determines the effectiveness and efficiency of a UUS system.

Experimental research (Cheng *et al.*, 1991; Gopalkrishnan *et al.*, 1994; Anderson, 1996; Anderson *et al.*, 1998) and computational studies (Streitlien and Triantafyllou, 1995; Streitlien *et al.*, 1996) have demonstrated that the relationships between the phase couplings of the heaving and pitching oscillations, with the interactions of the wakes/vortices shed from the body and the caudal aspects of the swimmer's body define the shape of the wake and the propulsive characteristics. The findings from these experimental and theoretical studies (Gopalkrishnan *et al.*, 1994; Anderson, 1996; Anderson *et al.*, 1998) have all acknowledged that the energy contained within the vortices shed from the body can be recaptured to enhance propulsive efficiency and / or increase the thrust generated.

To exploit this process the phase relationships between the heaving and pitching motions of the caudal aspects of the swimming body must be temporally coordinated to intercept the oncoming vortices generated by the body (Beal *et al.,* 2001; Beal, 2002). Triantafyllou *et al.* (2002), indicated that controlling vorticity is a major mechanism by which UUS performance and efficiency can be enhanced, as active control of the undulations/oscillations of the body and caudal aspects (tail / fluke) serve to eliminate flow separations, reduce turbulence and extract energy from oncoming flow.

The process by which the temporally coupled phase relationships between the heaving and pitching motions interact with the oncoming wake is directly related to optimisation of the wake structure produced from the trailing edge of the swimming body. The vorticity control at the trailing edge of the UUS body acts to shape the wake structure which is left behind the swimming body. A pattern of vortices is left in the flow following the UUS swimming body; these are shed from the trailing edge (tail/fluke/feet) at the deflection phases of the tail-beat or kick (2 per tail-beat / kick cycle). The amount of momentum imparted in the formation of these wakes and their direction of rotation is primarily dependent on the frequency and amplitude of the end-effector, and the angle of pitch of the trailing edge. The frequency of the oscillations also determines the distance between each of the vortices generated. The interaction of all these factors influences the orientation and propulsive capacity of the resultant wake structure.

There are several formalised names for commonly occurring wake structures (Karman street vortex, reverse-Karman street vortex, Rankine vortex profile, etc). Researchers (Barret *et al.*, 1999; Muller *et al.*, 2002; Triantafyllou *et al.*, 2002) have proposed that a reverse-Karman street vortex pattern is the most favourable wake structure for enhancing the effectiveness and efficiency of UUS performance (for more detailed descriptions of the other wakes structures see Müller *et al.* 2002). Triantafyllou *et al.* (2002) stated that the reverse Karman street vortex pattern occurs when two counter-rotating vortices are shed into the following wake, this results in the production of a jet flow which acts to enhance the propulsive impulse of the swimming body.

Triantafyllou *et al.* (1991, 1993) identified that the thrust-production capacity of the wake structure was related to how fast the vortices were being created and the space between them, and that it was optimised within a narrow range non-dimensional frequencies referred to as the Strouhal number (*St*). The Strouhal number can be defined as:

$$St = \frac{Af}{U} \tag{2}$$

where A is the width of the wake (approximated from the peak-to-peak amplitude of the trailing edge - tail / feet), f is the frequency of oscillation, and U is the mean swimming velocity.

From experimental studies of oscillating hydrofoils, Triantafyllou *et al.* (1991, 1993) and Streitlien and Triantafyllou (1998) have predicted a *St* range of 0.25-0.35; within which the optimisation of propulsive efficiencies occurs. Triantafyllou and Triantafyllou (1995) reason that the efficiency of animal UUS would also be optimised within the same *St* range. Barret *et al.* (1999) asserted that for *St* values outside this range, undulations of the body and caudal aspects of the swimming body can actually amplify AD up to 300% when compared to the AD experienced on the same body towed at the same swimming velocity. According to Lewin and Haj-Hariri (2000), at *St* values below the 0.25-0.35 range, viscous effects cause leading edge separation of the flow reducing both efficiency and thrust production. It is believed that at *St* values above the 0.25-0.35 range, power output and the production of a propulsive impulse is maximised at the expense of efficiency (Lewin and Haj-Hariri, 2000). Anderson *et al.* (1998) and Triantafyllou *et al.* (1993) found that the propulsive impulse was maximised between values of *St* ranging from 0.25 to 0.4. Both Anderson *et al.* (1998) and Triantafyllou *et al.* (1993) found that maximum efficiency was also achieved with the *St* range of 0.25 to 0.40. This minor disparity with the range of values for optimal thrust and those found by Lewin and Haj-Hariri (2000), could be as a consequence of the possible uncertainties in values of *St* which have been found in certain studies of aquatic UUS (Wolfgang *et al.*, 1999). Both Rosen (1959) and Wolfgang *et al.* (1999) suggested that these uncertainties are most likely a consequence of the natural variations in the kinematics of the swimming motions.

Even the most efficient performance of UUS in humans (with respect to the *St* values achieved) reported by Nicolas *et al.* (2007) (Table 2.3) was found to be outside the 0.40 limit normally associated with maximal efficiency in UUS. However, as stated at values above this range, power output and propulsive impulse are maximised at the expense of efficiency. Given the short lived requirements for such maximal efforts in a human form of UUS, one would expect to observe swimmers sacrificing efficiency in favour of an increased propulsive impulse.

Ungerechts *et al.* (2000) study of the vortex traces in human UUS has provided a number of practical implications for the control of vorticity along an UUS body which can be manipulated to optimise performance:

i. Vortex generation can be enhanced by whip-like action along the legs and feet.
ii. The reversal actions require well developed ankle flexibility to maximise whip-like actions.
iii. Hyper-extension at the knees can further increase the effectiveness of the whip-like action
iv. Vortex organisation is optimised if the amplitude of oscillations increases as the propulsive waveforms passes caudally along the body.

Table 2.3 Mean Strouhal values for animal and human UUS

Authors & Study Details	Species / Subjects	Strouhal Value Mean ± S.D.
Rohr & Fish (2004)		
Animals Trained to swim steadily behind a viewing panel. A total of 267 swimming sequences collected. Swimming velocities ranged between 2 - 8 m.s.$^{-1}$. Beluga whale (A much slower and less efficient swimmer) included for comparison.	**Odontocete Cetaceans**	
	Bottlenose Dolphin	St = 0.26 ± 0.05
	False Killer Whale	St = 0.26 ± 0.05
	Spotted Dolphin	St = 0.33 ± 0.03
	Stripped Dolphin	St = 0.24 ± 0.03
	Killer Whale	St = 0.28 ± 0.05
	Pilot Whale	St = 0.24 ± 0.02
	Beluga Whale	St = 0.35 ± 0.10
Arellano *et al.* (2002)		
International (n=19) swimmers and National (n=13) Age-Groups swimmers were compared performing UUS at maximal swimming velocity	International swimmers	St = 0.79
	National swimmers	St = 0.95
Lyttle and Keys (2004)		
CFD modelled UUS performance for large amplitude/slow kick and small amplitude/fast kick	Large amplitude /Slow kick	St = 0.57
	Small amplitude/ Fast kick	St = 0.52
Nicolas *et al.* (2007)		
12 French National Mono-fin swimmers recorded performing UUS with Mono-fins at maximal swimming velocity	Mono-fin Swimmers	St = 0.46± 0.11

S.D. Values are shown where reported in original research

All of the guidelines proposed by Ungerechts (2000) relate directly to the control of vorticity outlined previously (Anderson *et al.*, 1998; Triantafyllou *et al.*, 1993; Triantafyllou *et al.*, 2002), with the initiation and control of the dynamic eddying motions along the length of the swimming body and the effective manipulation of their transmission into the wake. However, Ungerechts (1984) warned that the direct application of all the vorticity control mechanisms observed in the highly efficient and effective animal UUS is limited due to the morphology of the human body

restricting movements in the dorso-ventral direction (i.e. limited range of motion at the knee joint), relative to the highly adapted aquatic species.

Irrespective of the caveats proposed by Ungerechts (1984), the findings of research directly related to specifically adapted, hydrodynamically efficient aquatic animals can offer insight into human forms of UUS. There is a lack of empirical research directly examining the influence of imposed movement frequencies on human maximal UUS performance. Given the highlighted importance of end-effector frequency in the animal literature, there is a clear requirement for empirical research to investigate the effects and influence of the imposition of an end-effector frequency on the coordination and performance in UUS. The knowledge gained from such research could be utilised to further optimise maximal UUS training and performance, thereby enhancing the underwater phases of the starts and turns in swimming races.

A greater understanding of the coordination involved in the production of effective and efficient UUS is required to determine if adaptations to performance can be achieved that further optimise UUS performance. The thesis investigates the inter and intra-limb coordination and its impact on the control of vorticity; most notably the phase relationships between the heaving and pitching movements of the feet, and the spatial and temporal structure of the movements involved in the production of the propulsive waveform. An examination of these elements of coordination will provide insight into whether human forms of UUS can effectively control the

undulations/oscillations of the body and orientation of the feet, to actively eliminate flow separations, reduce turbulence and extract energy from oncoming flow.

Finally, what is clear from the work presented within this review is that there is still a great deal of work required to fully understand the complexities of UUS performance, and to appreciate the potential opportunities for further UUS performance optimisation, especially in human UUS.

Chapter 3

Study 1:

Reliability of kinematic variables in maximal underwater undulatory swimming

3.1 Introduction

The UUS performed during the start and turns of swimming races is becoming an evermore popular topic for both performance analysis and empirical research (Mason and Cosser, 2000; Lyttle & Blanksby, 2000; Lyttle & Keys, 2004; Connaboy *et al.*,, 2007a; Connaboy *et al.*, 2007b). The underwater phase of the starts and turns are crucial sections of overall race performance. With the exception of the dive, the underwater phases of the starts and turns represent the fastest parts of the race. The component kinematic variables which are used to describe UUS are becoming more frequently assessed measures of performance, as exercise scientists, coaches and athletes seek to better understand UUS to evaluate and improve start, turn and overall swimming times.

The increasing assessment of UUS coupled with the growing popularity of UUS as a topic for research necessitates that the key kinematic components of UUS performance should be evaluated in terms of their reliability. Information and research evaluating the reliability of the kinematic variables used to describe and assess UUS are sparse, in particular there is little information regarding the relative contributions of systematic bias and/or Within-Subject (WS) variation pertaining to the reliability of specific UUS kinematic variables. Reliability in this instance refers to the consistency or repeatability of a specific measure of performance attained from repeated trials by the same individuals. A kinematic variable which is characterised by a small WS variation and a high test-retest correlation can be

regarded as reliable (Hopkins, 2000). A measure which is deemed reliable[1] can then be consider appropriate and precise enough to accurately track changes in the measurements for the purposes of research and/or in practical or applied settings (Hopkins, 2000). Without appreciating the reliability of each of the specific variables used to assess UUS, the sports scientist is unable to precisely identify the '*true*' value of that measure, and track any changes in said performance variable over time.

According to Hopkins (2000) and Hunter *et al.* (2004) reliability should be viewed and analysed in terms of its component parts, namely, (i) systematic bias, (ii) WS variation or 'random error', and (iii) the retest correlation. Systematic bias refers to the occurrence of a systematic or non-random change in the group mean (for a specific variable) between two or more trials (Hopkins, 2000). Factors such as fatigue, motivation and learning or practice effects can all contribute to the potential for the occurrence of a systematic bias. According to Hopkins *et al.*, (2001) once the magnitude and effects of the systematic bias are determined, researchers can instigate appropriate practices which minimise its occurrence (e.g. familiarisation trials to reduce the leaning effect).

The WS variation refers to the random error which occurs in repeated measurements of the same variable. Random error can include variations from several sources (biological, measurement errors, etc). However, the most common source of WS variation is biological variation (e.g. fluctuations in the expression of

[1] While validity is paramount, the validity of all the measures currently used to analyse UUS is beyond the scope of the current chapter, see the literature review chapter for details.

maximal force). Hopkins (2000), states that the WS variation is the most important type of reliability measure as it greatly influences the accuracy of an assessment of change in a specific variable within an experimental study. A smaller WS variation enables a more precise assessment of worthwhile changes in a variable.

The retest correlation, refers to the reproducibility of the rank order of the 'scores' or values of each individual within the sample, when a specific variable is repeatedly measured. Except where a single episode (trial or cycle) of performance is the principal focus of a study, it is considered that the use of multiple trials provides a more stable and representative account of biomechanical variation when compared to a single measurement (Bates *et al.,* 1983; Bates *et al.,* 1992; James *et al.,* 2007). According to Portney and Watkins (2000) test-retest reliability methods are commonly used to evaluate the stability or repeatability of a specific variable across repeated trials.

The number of trials used to assess baseline levels of performance and/or a subsequent change in performance (i.e. post intervention), is an important methodological consideration (James *et al.,* 2007). The stability of the mean value of multiple trials is greatly influenced by the stability of the variation across trials. If insufficient trials are used to ascertain a 'true' representative mean value for a specific variable, then the reported mean value of the collected trials will not accurately represent the performance. Consequently, the validity of the specific variable to assess performance would be limited. Both Bates *et al,* (1983) and Salo *et al.* (1997) highlight the requirement for empirical work to be undertaken to

ascertain the number of trials necessary to provide stable, representative data, prior to analysing performance. Without such *apriori* investigations, empirical research investigating changes in said variables to assess overall performance, could produce results that falsely support a null-hypothesis as a result of insufficient statistical power (Bates *et al.,* 1992). Consequently, the assessment of systematic bias, random error and retest correlation, can go some way to address the issues highlighted by Bates *et al.,* (1992). By examining the WS variation apparent in the specific population, clarifying the extent of any learning, practice and/or fatigue effects associated with repeated collection of the specified variables, and ascertaining the requisite number of trials required to accurately determine WS variation, the factors influencing statistical power can be adequately addressed.

Thus the purpose of this study was to determine the reliability of the kinematic variables of interest in UUS. To this end three specific aims were addressed: (1) determine the extent of any systematic bias between session, trial and/or cycle, (2) establish the WS variation of the key biomechanical measures commonly used to assess maximal UUS performance in skilled swimmers, and (3) ascertain the number of cycles/trials required to obtain stable levels of variability and high levels of reliability in the maximal UUS kinematics.

3.2 Methods

3.2.1 Participants

The participants were fifteen skilled male swimmers (Mean ± S.D: Age 19 ± 3.3 years, Height 1.82 ± 0.05 m, Weight 74.8 ± 8.6 kg, Competitive swimming experience 9.4 ± 3.2 years) from the Edinburgh University swimming team. Ethical approval was gained from the Edinburgh University ethics committee. Written informed consent was obtained from each participant (Appendix 1 and 2).

3.2.2 Study Design

A single group, repeated-measure study design was employed to assess the requirement for familiarisation trials, determine the reliability of the kinematic variables in maximal UUS, and calculate the number of cycles required to accurately represent each kinematic variable. During each session participants completed five trials of maximal UUS. All participants attended four testing sessions, with each testing session separated by seven days. The trials were repeated at the same time of day on each of the four testing sessions to minimise the influence of diurnal biological variation on performance (Reilly, Robinson and Minors, 1984). Participants were also asked not to practice the task throughout the four week testing period and asked to refrain from strenuous exercise 24-hours prior to each session.

3.2.3 Experimental Protocol

Before entering the water participants were marked with circles of black oil based body paint (3cm diameter) at the joint centres of the wrist, shoulder, hip, knee,

ankle and 5th metatarsal phalangeal joint (5th MPJ) of the foot on the right side of the body. Prior to undertaking the maximal UUS trials each swimmer performed a standardised twenty-minute warm-up at the beginning of each testing session. Each performance trial consisted of the participant swimming 15m underwater using an UUS technique. Each trial started with the participant in the water; a push-start off the wall was performed to reach a designated depth (approx. 0.60-1.0 m) below the surface of the water to negate the effects of wave drag (Vennell, *et al.,* 2006).

Swimmers were instructed to perform a sub-maximal push start off the wall to reduce the impact of variations in push-start performance on UUS kinematics variables measured. The push off from the wall was used to achieve the correct depth and orientation (horizontal with respect to the camera), not as a means to maximise swimming velocity. Once the required depth and orientation were achieved, swimmers were then required to accelerate towards a marker on the pool floor 10m away, representing the start of the filming area. Participants were instructed to maximise swimming velocity as they passed over the first marker and maintain max U throughout the designated filming area until they passed over a second marker, a further 5 m ahead. To conform with common convention participants swam from left to right through the filming area.

Filming procedure

A two-dimensional cinematographic technique was employed to collect position-time data. The participants were filmed with a stationary underwater camera (KY32 CCD; JVC Corporation, Yokohama, Japan) at fifty fields per second. The optical

axis of the camera was perpendicular to the plane of motion of the swimmer. The camera was fixed at a distance of 12 m from the plane of motion of the swimmer (see Figure 4.1) 1 m below the surface of the water, this allowed a data capture window of 4 m in the horizontal plane and ensuring that a minimum of two complete kick cycles could be captured within the allotted filming area. Two cycles per trial were captured to allow the between cycle (within-trial) variations in kinematics (velocity, kick amplitude, etc) to be assessed. Participants repeated the procedure a total of five times per session, with a five minute rest interval between trials to minimise the effects of fatigue. In accordance with common convention the swimmers were instructed to swim from left to right through the filming area.

Digitising

Two consecutive kick cycles from each trial were measured for each participant. The segment endpoint data from each kick cycle were digitised using Ariel Performance Analysis System (APAS-2000 Ariel Dynamics, 2000). A kick cycle was defined from the video data as the frame corresponding to the initiation of an upward movement at the 5th MPJ, through a complete kick cycle, to the frame immediately preceding the frame corresponding to the initiation of an upward movement at the 5th MPJ for a second kick cycle. Fifteen additional frames either side of the observed start and end of the two kick cycles were digitised to enable the accurate identification of the start/end points of each cycle, to avoid distortion in the calculation of time derivates of position data (Vaughan, 1982) and provide additional data points to minimise errors associated with endpoint errors when smoothing data (Vint and Hinrichs, 1996).

The raw screen coordinate data output were extracted from the APAS system using a specifically designed Visual Basic (Visual Basic 4.0) programme (Coleman, 2000). This enabled the pixel to real world vertical and horizontal ratios to be determined and scale factors adjusted accordingly. These data were then transformed to produce the raw displacement data, using a participant derived two-dimensional linear scale (Clothier *et al.,* 2004), whereby each cycle of the collected video data was calibrated with respect to a scale factor determined from a reference structure of known dimension (thigh length) present within each frame of the video data. To minimise distortion of the data as a consequence of the swimmers swimming 'out of plane', any swimming trial which deviated from the required line of swimming was not included for further analysis. For the purpose of this analysis bilateral symmetry was assumed (Sanders *et al.,* 1996; Connaboy *et al.,* 2010) and only the side of the body facing the camera (right hand side) was digitised to define a five segment model of the swimmer's body, comprising the arm, trunk, thigh, shank and foot.

The digitised coordinates of the raw 2D segment endpoint data were filtered using a Fourier transform as it represents an appropriate filter for cyclical kinematic data if the key assumptions of the Fourier transform (cyclical data with a consistent starting point and a mean of zero across each cycle) are met (Winter, 2009). To satisfy the prerequisite conditions of the Fourier transform the raw data were demeaned and detrended prior to filtering. The digitised coordinates of the raw 2D segment endpoint data were smoothed (7 Hz) using a truncated Fourier transform.

A cut-off frequency for filtering the data was selected at 7 Hz, as more than 98% of the power in the displacement-time signals was contained within the harmonics up to 7 Hz and frequencies higher than the cut-off frequency would be attributable to random errors associated with the digitising process.

Data Processing

The displacement data were input to a specifically designed MATLAB (Mathworks, Inc) programme (Connaboy & Sanders, 2004). As the sampling frequency was limited to 50 Hz, the cycle time could only be calculated to the nearest 0.02 of a second. To ascertain the cycle frequency more precisely the whole filtered data sequence comprising two cycles plus the fifteen frames prior to and following the two cycles, were interpolated to a 200 Hz sampling rate by setting the number of data points in the inverse transform to four times the number in the original data set, so allowing the start/end points of each kick cycle to be identified to the nearest 0.005 of a second. The programme then calculated the first two derivatives (velocity and acceleration) of the displacement data for the shoulder, hip, knee, ankle and 5th MPJ by differentiation using central difference formulae after restoring the mean and slope to the inverse transform data. The start/end points of each kick cycle were then identified based on the four local minima of the y-axis coordinates of the 5th MPJ data. These points represent the minimum vertical displacement values of the foot throughout the two cycles. After ascertaining precise measures of cycle frequency for the whole data sequence of two cycles, the trial displacement, velocity and acceleration data were then

separated into the two cycles by the minimum values stated. The additional frames included to minimise the effects of endpoint errors were also removed at this time.

3.2.4 Data analysis

A total of nineteen individual kinematic variables commonly used to analyse UUS were calculated for each kick cycle. Each of the variables incorporated in the study have previously been identified as being important in the execution of UUS (see section 2.3):

Maximum UUS velocity (max *U*)

The average horizontal hip velocity over each cycle of the maximum UUS trial was used as a representation of max *U* for each cycle. The average horizontal velocity of the hip was obtained for each kick cycle and calculated as the difference in the horizontal displacement of the hip throughout a kick cycle divided by the time taken to complete the cycle, with displacement values obtained from the APAS output.

$$max\ U = (d_2 - d_1)/t \tag{3}$$

where max *U* is the average swimming velocity, d_2 and d_1 are the final and initial horizontal displacements of the hip, respectively, and t is the time taken to complete one kick cycle.

End-effector kicking frequency (EE_Hz).

End-effector kicking frequency was calculated as the inverse of the time taken to complete a kick cycle.

$$EE\_Hz = 1/t \tag{4}$$

where EE_Hz is the cycle frequency and t is the time taken to complete one kick cycle.

Cycle length (CL).

Cycle length was calculated as the horizontal displacement of the hip marker over one complete kick cycle.

Range of movement (ROM) and maximum joint angular velocity.

The minimum and maximum angular displacements of each of the relevant joints were calculated from the angular displacement data and the ROM calculated as the difference between these two values for each of the respective joints. The joint angle was defined as the angle formed at the joint by the movement of the component limbs (see Figure 3.1). Maximum angular velocity was derived from the angular displacement data.

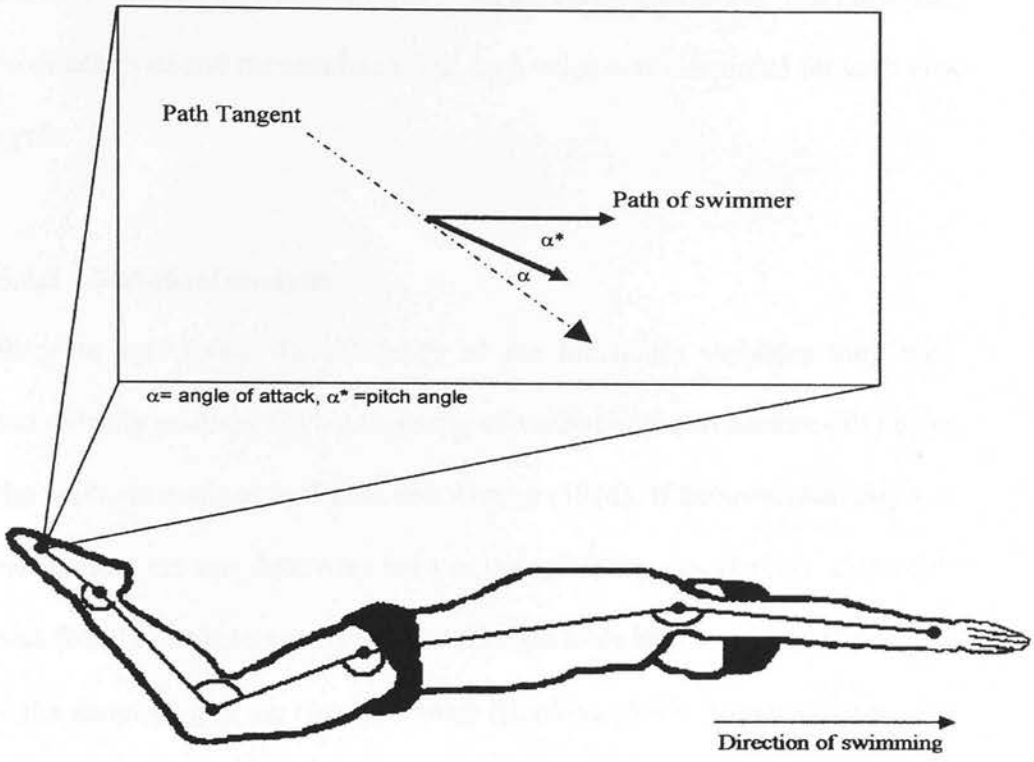


Figure 3.1 Subject joint centre markings and Joint angle definitions and the calculations of AoA.

Joint centre amplitude (JCA).

Amplitude of the oscillations of the joint centres at the wrist, shoulder, hip, knee, ankle and 5th MPJ were calculated. The amplitudes were calculated as the difference between the maximum and minimum values from the vertical displacements of the segment endpoint data

Angle of attack (AoA).

Angle of attack was determined from the filtered segment endpoint data of the ankle joint and the 5th MPJ. The AoA was calculated as the angle between the tangent of the path of the foot and angle of the foot (see Figure

3.1) at every sampled instant throughout the entire kick cycle. The maximum AoA achieved and the absolute mean AoA value was calculated for each kick cycle.

3.2.5 Statistical analysis

Prior to calculating the reliability of the kinematic variables they were individually assessed for homogeneity of variances (heteroscedasticity) using the methods outlined by Bland and Altman (1986). If heteroscedasticity was not present the raw data were used in the reliability calculations. If the data was found to be heteroscedastic then the data were log-transformed using 100 × the natural log of the observed value (Hopkins, 2000). Systematic bias was determined using repeated-measure analysis of variance (RM ANOVA). A series of RM ANOVAs were completed to calculate the magnitude of difference apparent between the mean values for each session (n= 4), trial (n=5) and cycle (n=2). Alpha was set at 0.05. Any significant inter-session, trial or cycle differences were assessed from the planned comparisons using the Bonferroni procedure. Where any statistically significant differences occurred those sessions, trials, cycles were removed from further calculations of reliability (random-error/test-retest).

WS variation was calculated for 3, 4, 5, 6, 12, 18, 24 and 30 cycles, as both typical error (TE) and coefficient of variation (CV).

Typical error was calculated as,

$$TE = \sqrt{MSE_n} \tag{5}$$

where, MSE_n is the mean square error value from the RM ANOVA from *n* repeated cycles.

The coefficient of variation was determined as,

$$CV_{TE} = \left(\frac{TE_n}{M_n} \right) \times 100 \tag{6}$$

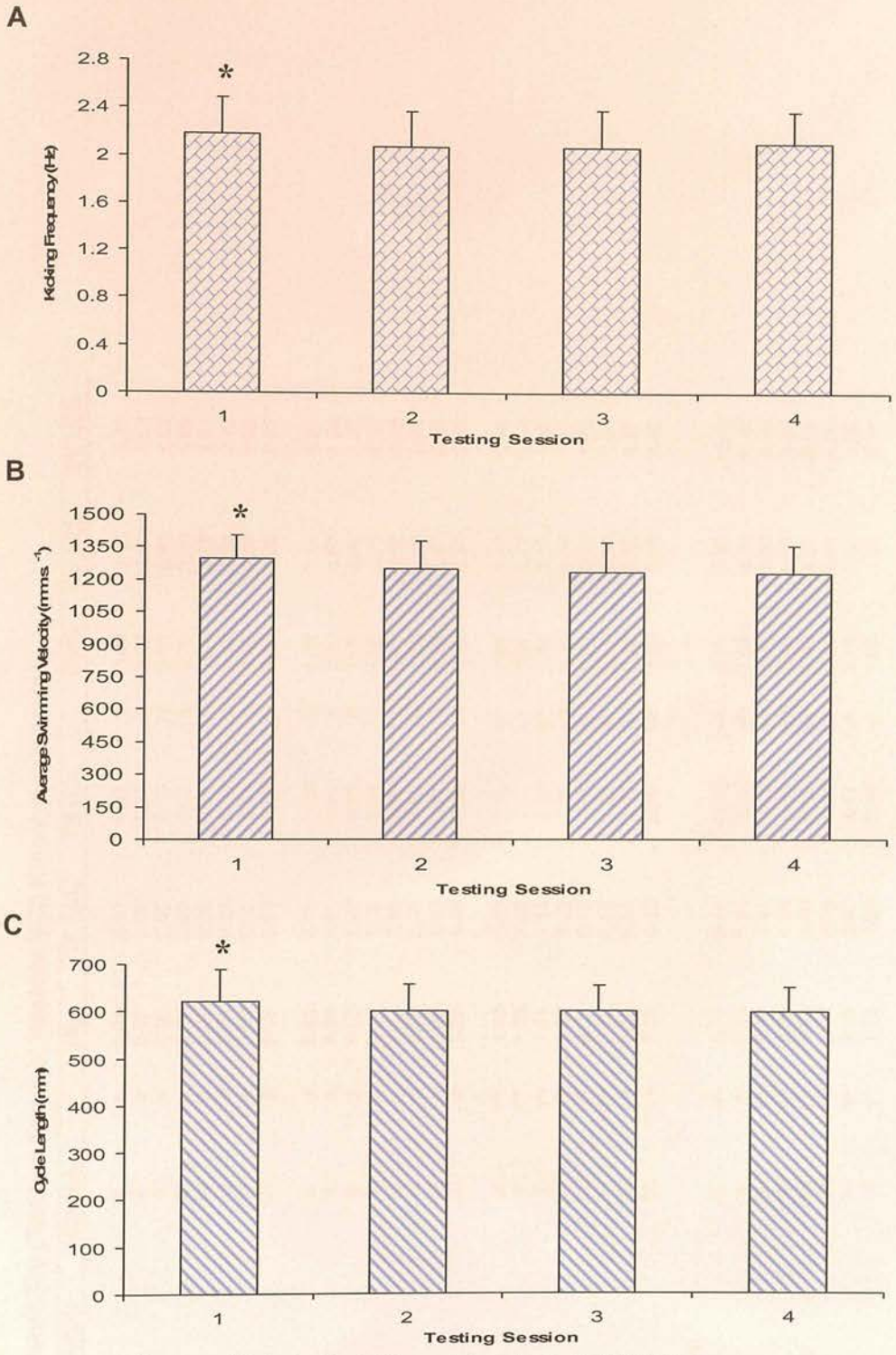
where, TE_n is the typical error of *n* number of cycles and M_n is the mean value from the same *n* repeated cycles. Confidence limits (95%) for CV were calculated using the methods outlined by Tate and Klett (1959).

The test-retest reliability for all the remaining cycles was evaluated using a mixed-model (3,1) intra-class correlation coefficient (ICC) (Morrow and Jackson, 1993). The stability of the variation in each kinematic variable was assessed using the methods proposed by James *et al.* (2007). The initial ICC was determined for two cycles. An iterative process was then conducted, whereby repeated ICC's were performed including an additional cycle within each iteration. The maximum ICC value for all cycles and the 95% confidence intervals (upper and lower limits) were calculated. Confidence limits (95%) for the ICC were calculated using the methods outlined by McGraw and Wong (1996). To assess the stability of each variable, the

minimum number of cycles required to achieve the maximum ICC value was calculated. To determine the minimum number of cycles required to achieve a stable representation of the variation within each of the kinematic variables the number of cycles required to achieve ICC values of 0.85, 0.90 and 0.95 were also calculated.

3.3 Results

Statistically significant differences between testing sessions were found for max *U* (p=0.049), EE_Hz (p=0.045) and CL (p=0.044). Results from the Bonferroni planned comparisons indicated systematic bias between the first and the remaining three testing sessions for max *U*, EE_Hz and CL. Figure 3.2 highlights the differences in mean values between session 1 and the following three sessions for max *U*, EE_Hz, and CL. No significant differences were found in mean values across the four testing sessions for any of the remaining kinematic variables. No significant differences in mean values were found across trial or cycle for any of the remaining kinematic variables. To remove the effects of the systematic bias between session one and the remaining three sessions, only the data from the final three testing sessions (thirty cycles) were included in the subsequent reliability analyses (random error/test-retest). Table 3.1 shows the results for the within subject variation. Depending on whether or not heteroscedasticity was present, random error was expressed in either absolute or ratio form.



Note * indicates a statistically significant difference between Session ($p<0.05$). Values are session means: error bars are sample standard deviations.

Figure 3.2 Reliability (Systematic Error) of Maximal UUS Kinematic Variables. Mean values for session (1-4) for (A) Kicking Frequency (EE_Hz), (B) Max *U* and (C) Cycle Length.

Table 3.1 Reliability (Random Error) of Maximal UUS Kinematic Variables.

Variable (Units or Ratio)	$Cycles_{(n)}$		$TE_{(n)}$	TE LCL	TE UCL		CV%	CV LCL	CV UCL
EE_Hz (Hz)	3	±	0.08	0.07	0.11	±	3.89	3.10	5.23
	4	±	0.07	0.06	0.10	±	3.37	2.68	4.53
	5	±	0.06	0.05	0.09	±	3.01	2.40	4.05
	6	±	0.06	0.05	0.08	±	2.75	2.19	3.69
	12	±	0.04	0.03	0.05	±	1.94	1.55	2.61
	18	±	0.03	0.03	0.04	±	1.59	1.26	2.13
	24	±	0.03	0.02	0.04	±	1.37	1.09	1.85
	30	±	0.02	0.01	0.02	±	0.79	0.68	0.95
Cycle Length (mm)	3	±	8.43	6.71	11.33	±	1.41	1.12	1.90
	4	±	7.30	5.81	9.81	±	1.22	0.97	1.64
	5	±	6.53	5.20	8.78	±	1.09	0.87	1.47
	6	±	5.96	4.75	8.01	±	1.00	0.79	1.34
	12	±	4.21	3.36	5.67	±	0.71	0.56	0.95
	18	±	3.44	2.74	4.63	±	0.58	0.46	0.77
	24	±	2.98	2.37	4.01	±	0.50	0.40	0.67
	30	±	1.72	1.48	2.06	±	0.29	0.25	0.35
Max *U* (Ratio)	3	×/÷	1.83	1.45	2.45	×/÷	1.84	1.47	2.48
	4	×/÷	1.58	1.26	2.13	×/÷	1.59	1.27	2.14
	5	×/÷	1.41	1.13	1.90	×/÷	1.42	1.13	1.92
	6	×/÷	1.29	1.03	1.74	×/÷	1.30	1.04	1.75
	12	×/÷	0.91	0.73	1.23	×/÷	0.92	0.73	1.23
	18	×/÷	0.75	0.59	1.00	×/÷	0.75	0.60	1.01
	24	×/÷	0.65	0.51	0.87	×/÷	0.65	0.52	0.87
	30	×/÷	0.37	0.32	0.45	×/÷	0.37	0.32	0.45
Range of Movement									
Shoulder (Ratio)	3	×/÷	8.77	6.99	11.79	×/÷	9.17	7.30	12.32
	4	×/÷	7.60	6.05	10.21	×/÷	7.89	6.29	10.61
	5	×/÷	6.79	5.41	9.13	×/÷	7.03	5.60	9.45
	6	×/÷	6.20	4.94	8.34	×/÷	6.40	5.10	8.60
	12	×/÷	4.39	3.49	5.90	×/÷	4.48	3.57	6.03
	18	×/÷	3.58	2.85	4.81	×/÷	3.65	2.90	4.90
	24	×/÷	3.10	2.47	4.17	×/÷	3.15	2.51	4.23
	30	×/÷	1.79	1.54	2.14	×/÷	1.80	1.55	2.16

Variable (Units or Ratio)	$Cycles_{(n)}$		$TE_{(n)}$	TE LCL	TE UCL		CV%	CV LCL	CV UCL
Hip (Ratio)	3	×/÷	2.88	2.29	3.87	×/÷	2.92	2.32	3.92
	4	×/÷	2.49	1.98	3.35	×/÷	2.52	2.01	3.39
	5	×/÷	2.23	1.77	3.00	×/÷	2.25	1.79	3.03
	6	×/÷	2.03	1.62	2.73	×/÷	2.05	1.64	2.76
	12	×/÷	1.44	1.15	1.93	×/÷	1.45	1.15	1.95
	18	×/÷	1.17	0.94	1.58	×/÷	1.18	0.94	1.59
	24	×/÷	1.02	0.81	1.37	×/÷	1.02	0.81	1.37
	30	×/÷	0.59	0.50	0.70	×/÷	0.59	0.51	0.71
Knee (°)	3	±	1.16	0.93	1.56	±	1.21	0.97	1.63
	4	±	1.01	0.80	1.35	±	1.05	0.84	1.41
	5	±	0.90	0.72	1.21	±	0.94	0.75	1.26
	6	±	0.82	0.66	1.11	±	0.86	0.68	1.15
	12	±	0.58	0.46	0.78	±	0.61	0.48	0.82
	18	±	0.48	0.38	0.64	±	0.50	0.39	0.67
	24	±	0.41	0.33	0.55	±	0.43	0.34	0.58
	30	±	0.24	0.20	0.28	±	0.25	0.21	0.30
Ankle (°)	3	±	1.72	1.37	2.31	±	3.92	3.12	5.27
	4	±	1.49	1.18	2.00	±	3.40	2.71	4.57
	5	±	1.33	1.06	1.79	±	3.04	2.42	4.08
	6	±	1.21	0.97	1.63	±	2.77	2.21	3.73
	12	±	0.86	0.68	1.15	±	1.96	1.56	2.64
	18	±	0.70	0.56	0.94	±	1.60	1.28	2.15
	24	±	0.61	0.48	0.82	±	1.39	1.10	1.86
	30	±	0.35	0.30	0.42	±	0.80	0.69	0.96
Angle of Attack									
Max AoA (°)	3	±	1.45	1.16	1.96	±	1.81	1.44	2.44
	4	±	1.26	1.00	1.69	±	1.57	1.25	2.11
	5	±	1.13	0.90	1.51	±	1.40	1.12	1.89
	6	±	1.03	0.82	1.38	±	1.28	1.02	1.72
	12	±	0.73	0.58	0.98	±	0.91	0.72	1.22
	18	±	0.59	0.47	0.80	±	0.74	0.59	0.99
	24	±	0.51	0.41	0.69	±	0.64	0.51	0.86
	30	±	0.29	0.26	0.36	±	0.37	0.32	0.44

Variable (Units or Ratio)	$Cycles_{(n)}$		$TE_{(n)}$	TE LCL	TE UCL		CV%	CV LCL	CV UCL
Mean (Absolute) AoA (Ratio)	3	×/÷	1.68	1.34	2.26	×/÷	1.69	1.35	2.28
	4	×/÷	1.45	1.16	1.95	×/÷	1.46	1.17	1.97
	5	×/÷	1.30	1.04	1.75	×/÷	1.31	1.04	1.76
	6	×/÷	1.19	0.95	1.60	×/÷	1.19	0.95	1.60
	12	×/÷	0.84	0.67	1.13	×/÷	0.84	0.67	1.13
	18	×/÷	0.69	0.55	0.92	×/÷	0.69	0.55	0.92
	24	×/÷	0.59	0.47	0.80	×/÷	0.60	0.47	0.80
	30	×/÷	0.34	0.29	0.41	×/÷	0.34	0.30	0.41
Joint Centre Amplitudes									
Wrist (Ratio)	3	×/÷	12.09	9.63	16.25	×/÷	12.85	10.23	17.27
	4	×/÷	10.47	8.34	14.07	×/÷	11.03	8.79	14.83
	5	×/÷	9.36	7.46	12.58	×/÷	9.81	7.82	13.19
	6	×/÷	8.55	6.81	11.49	×/÷	8.92	7.11	11.99
	12	×/÷	6.04	4.81	8.12	×/÷	6.23	4.96	8.37
	18	×/÷	4.93	3.93	6.63	×/÷	5.06	4.03	6.80
	24	×/÷	4.27	3.40	5.74	×/÷	4.37	3.48	5.87
	30	×/÷	2.47	2.12	3.00	×/÷	2.50	2.15	2.99
Shoulder (Ratio)	3	×/÷	8.31	6.61	11.16	×/÷	8.66	6.90	11.64
	4	×/÷	7.19	5.73	9.67	×/÷	7.46	5.94	10.03
	5	×/÷	6.43	5.12	8.65	×/÷	6.64	5.29	8.93
	6	×/÷	5.87	4.68	7.89	×/÷	6.05	4.82	8.13
	12	×/÷	4.15	3.31	5.58	×/÷	4.24	3.38	5.70
	18	×/÷	3.39	2.70	4.56	×/÷	3.45	2.75	4.64
	24	×/÷	2.94	2.34	3.95	×/÷	2.98	2.37	4.01
	30	×/÷	1.70	1.46	2.03	×/÷	1.71	1.47	2.05
Hip (Ratio)	3	×/÷	4.99	3.98	6.71	×/÷	5.12	4.08	6.88
	4	×/÷	4.32	3.44	5.81	×/÷	4.42	3.52	5.94
	5	×/÷	3.87	3.08	5.20	×/÷	3.94	3.14	5.30
	6	×/÷	3.53	2.81	4.75	×/÷	3.59	2.86	4.83
	12	×/÷	2.50	1.99	3.36	×/÷	2.53	2.01	3.40
	18	×/÷	2.04	1.62	2.74	×/÷	2.06	1.64	2.77
	24	×/÷	1.77	1.41	2.37	×/÷	1.78	1.42	2.39
	30	×/÷	1.02	0.88	1.22	×/÷	1.02	0.88	1.23

Variable (Units or Ratio)	$Cycles_{(n)}$		$TE_{(n)}$	TE LCL	TE UCL		CV%	CV LCL	CV UCL
Knee (mm)	3	±	9.12	7.26	12.26	±	3.02	2.40	4.06
	4	±	7.90	6.29	10.62	±	2.61	2.08	3.51
	5	±	7.07	5.63	9.50	±	2.34	1.86	3.14
	6	±	6.45	5.14	8.67	±	2.13	1.70	2.87
	12	±	4.56	3.63	6.13	±	1.51	1.20	2.03
	18	±	3.72	2.97	5.01	±	1.23	0.98	1.66
	24	±	3.23	2.57	4.34	±	1.07	0.85	1.43
	30	±	1.86	1.60	2.23	±	0.61	0.53	0.74
Ankle (Ratio)	3	×/÷	2.14	1.71	2.88	×/÷	2.16	1.72	2.91
	4	×/÷	1.85	1.48	2.49	×/÷	1.87	1.49	2.52
	5	×/÷	1.66	1.32	2.23	×/÷	1.67	1.33	2.25
	6	×/÷	1.51	1.21	2.04	×/÷	1.53	1.22	2.05
	12	×/÷	1.07	0.85	1.44	×/÷	1.08	0.86	1.45
	18	×/÷	0.87	0.70	1.18	×/÷	0.88	0.70	1.18
	24	×/÷	0.76	0.60	1.02	×/÷	0.76	0.61	1.02
	30	×/÷	0.44	0.38	0.52	×/÷	0.44	0.38	0.52
5th MPJ (mm)	3	±	11.40	9.08	15.32	±	1.81	1.44	2.44
	4	±	9.87	7.86	13.27	±	1.57	1.25	2.11
	5	±	8.83	7.03	11.87	±	1.40	1.12	1.89
	6	±	8.06	6.42	10.83	±	1.28	1.02	1.72
	12	±	5.70	4.54	7.66	±	0.91	0.72	1.22
	18	±	4.65	3.71	6.26	±	0.74	0.59	0.99
	24	±	4.03	3.21	5.42	±	0.64	0.51	0.86
	30	±	2.33	2.78	2.00	±	0.37	0.32	0.44
Maximum Angular Velocities									
Shoulder Angular Velocity (Ratio)	3	×/÷	9.24	7.36	12.42	×/÷	9.68	7.71	13.01
	4	×/÷	8.00	6.37	10.76	×/÷	8.33	6.63	11.20
	5	×/÷	7.16	5.70	9.62	×/÷	7.42	5.91	9.97
	6	×/÷	6.53	5.20	8.78	×/÷	6.75	5.38	9.08
	12	×/÷	4.62	3.68	6.21	×/÷	4.73	3.77	6.36
	18	×/÷	3.77	3.00	5.07	×/÷	3.84	3.06	5.17
	24	×/÷	3.27	2.60	4.39	×/÷	3.32	2.64	4.46
	30	×/÷	1.89	1.62	2.26	×/÷	1.90	1.64	2.28

Variable (Units or Ratio)	$Cycles_{(n)}$		$TE_{(n)}$	TE LCL	TE UCL		CV%	CV LCL	CV UCL
Hip Angular Velocity (Ratio)	3	×/÷	6.14	4.89	8.25	×/÷	6.33	5.04	8.51
	4	×/÷	5.31	4.23	7.14	×/÷	5.46	4.35	7.34
	5	×/÷	4.75	3.79	6.39	×/÷	4.87	3.88	6.54
	6	×/÷	4.34	3.46	5.83	×/÷	4.43	3.53	5.96
	12	×/÷	3.07	2.44	4.12	×/÷	3.12	2.48	4.19
	18	×/÷	2.51	2.00	3.37	×/÷	2.54	2.02	3.41
	24	×/÷	2.17	1.73	2.92	×/÷	2.19	1.75	2.95
	30	×/÷	1.25	1.08	1.50	×/÷	1.26	1.08	1.51
Knee Angular Velocity (°.s-1)	3	±	15.66	12.47	21.05	±	2.05	1.63	2.75
	4	±	13.56	10.80	18.23	±	1.77	1.41	2.38
	5	±	12.13	9.66	16.31	±	1.59	1.26	2.13
	6	±	11.07	8.82	14.89	±	1.45	1.15	1.95
	12	±	7.83	6.24	10.53	±	1.02	0.81	1.38
	18	±	6.39	5.09	8.59	±	0.84	0.67	1.12
	24	±	5.54	4.41	7.44	±	0.72	0.58	0.97
	30	±	3.20	2.75	3.83	±	0.42	0.36	0.50
Ankle Angular Velocity (°.s-1)	3	±	22.29	17.75	29.97	±	4.98	3.96	6.69
	4	±	19.31	15.37	25.95	±	4.31	3.43	5.80
	5	±	17.27	13.75	23.21	±	3.86	3.07	5.18
	6	±	15.76	12.55	21.19	±	3.52	2.80	4.73
	12	±	11.15	8.88	14.98	±	2.49	1.98	3.35
	18	±	9.10	7.25	12.23	±	2.03	1.62	2.73
	24	±	7.88	6.28	10.60	±	1.76	1.40	2.37
	30	±	4.55	3.91	5.45	±	1.02	0.87	1.22

Note. $TE_{(n)}$ – Typical Error for *n* cycles. CV% - percentage Coefficient of Variation. LCL (Lower Confidence Limit), UCL (Upper Confidence Limit). ± indicates that the random error is represented in absolute form. ×/÷ indicates that the random error is represented in ratio form.

The results presented in Table 3.1 illustrate that the extent of random error within the respective kinematic variables varies markedly (i.e. Knee ROM for 3 cycles: CV=1.21% compared to Wrist joint centre amplitude for three cycle: CV=12.85%). Irrespective of the relative differences in random error for each of the variables, the reliability was found to increase as the number of trials used to determine the average score increased (from n=3 to n=30). The greatest increases in reliability (reduction in CV%) were apparent within the initial changes in the number of trials used to calculate the mean value, with an average of 0.59 CV% reduction in CV% by using four cycles compared to three, a further 0.40 CV% average reduction by using five compared to four, and a further 0.37 CV% average reduction in CV% by using six cycles compared to five. Beyond six cycles, the use of additional cycles of data to calculate the mean value resulted in diminishing returns; for every additional cycle used in the calculation of the mean values the smaller the reduction in the CV%.

The data presented in Table 3.2 show the levels of performance stability achieved for each of the kinematic variable measured. The maximum ICC value recorded (0.996) was for max U, with the maximum ICC values ranging from 0.952 to 0.996. The number of cycles required to reach the maximum ICC values ranged from three to twenty-three (mean 9.74 ± 5.63 cycles). With the exception of the Knee JCA, all variables achieved an ICC values of 0.90 (or greater) after three cycles, and all except Knee JCA attained an ICC value of 0.95 (or greater) after six cycles. The number of cycles required for all kinematic variables to achieve an ICC value of 0.95 ranged from two to eleven (mean 3.57 ± 2.09 cycles).

Table 3.2 Reliability (Retest Reliability) of Maximal UUS Kinematic Variables.

Variable (Unit or Ratio)	ICC Maximum (n-cycles)	ICC	ICC 95% LCL	ICC 95% UCL	ICC 0.85 (n-cycles)	ICC 0.90 (n-cycles)	ICC 0.95 (n-cycles)
EE_Hz (Hz)	6	0.993	0.986	0.997	2	3	3
Cycle Length (mm)	9	0.985	0.971	0.994	2	3	3
Max *U* (Ratio)	3	0.996	0.991	0.998	2	2	2
Range of Movement							
Shoulder (Ratio)	10	0.988	0.976	0.995	2	2	3
Hip (Ratio)	6	0.994	0.988	0.998	2	2	2
Knee (°)	9	0.988	0.978	0.996	2	2	3
Ankle (°)	5	0.993	0.987	0.997	2	2	3
Angle of Attack							
Max AoA (°)	14	0.987	0.974	0.995	2	3	4
Mean (Absolute) AoA (Ratio)	7	0.992	0.985	0.997	2	2	3
Joint Centre Amplitudes							
Wrist (Ratio)	10	0.979	0.959	0.992	3	3	3
Shoulder (Ratio)	21	0.971	0.944	0.989	2	3	6
Hip (Ratio)	15	0.986	0.972	0.995	2	2	4
Knee (mm)	23	0.952	0.908	0.982	6	7	11
Ankle (Ratio)	7	0.988	0.977	0.995	2	2	2
5th MPJ (mm)	6	0.989	0.978	0.996	2	2	2
Maximum Angular Velocities							
Shoulder Angular Velocity (Ratio)	15	0.987	0.974	0.995	2	2	5
Hip Angular Velocity (Ratio)	4	0.994	0.988	0.998	2	2	3
Knee Angular Velocity (°.s^{-1})	9	0.993	0.987	0.997	3	3	4
Ankle Angular Velocity (°.s^{-1})	6	0.994	0.989	0.998	2	2	2
Mean (SD)	9.74 (5.63)				2.33 (0.97)	2.61 (1.2)	3.57 (2.09)

Note. ICC-Intra-class Correlation Coefficient. ICC Maximum refers to the number of cycles necessary to achieve the ICC value attained for the maximum number of cycles (n=30). LCL (Lower Confidence Limit), UCL (Upper Confidence Limit). ICC 0.85, ICC 0.90 and ICC 0.95 refer to the number of cycles required to achieve the respective ICC value.

3.4 Discussion

The purpose of this study was to determine the reliability of the kinematic variables of interest in UUS. To this end three specific aims were addressed: The first of those aims was to determine the existence of any systematic bias between session, trial and/or cycle, to evaluate the extent of any learning, motivation and/or fatigue effects. The results of the study clearly indicate the requirement of a single familiarisation session prior to collecting sufficiently reliable kinematic data. The systematic, and statistically significant ($p<0.05$) changes in the mean between session one and the remaining three sessions for max *U*, EE_Hz, and CL suggest that for this specific experimental protocol, familiarisation is required before a reliable representation of the '*true*' values of these three key kinematic variables are attained.

The requirement for further familiarisation and practice of a skill commonly undertaken by swimmers may at first appear counter intuitive. However, the protocol used to acquire the UUS kinematic data is relatively novel compared to the normal UUS practices within training and/or racing. While skilled swimmers may be accustomed to turning off the wall and performing maximal UUS, the protocol used within the present study required that the swimmers did not utilise the push-off from the wall to maximise swimming velocity, rather simply to attain the required depth and orientation. The present protocol enabled the UUS performance to be isolated from any variation in the execution of the push-off from the wall. This difference/novel aspect of the protocol may have resulted in the values recorded. As it can be seen from figure 3.2, max *U*, EE_Hz and CL were significantly greater in session one compared to the remaining three sessions, representing the learning

required before the swimmers could successfully adhere to experimental protocol and not use the wall to maximise swimming velocity.

No significant differences were found between trials for any of the kinematic variables. This suggests that the five trials conducted per session with five minutes recovery between each trial did not cause levels of fatigue sufficient enough to alter the kinematics of the UUS significantly. Likewise, the results also indicate that there was no learning effect present between trials and that the motivation to produce maximal UUS performance over the five trials was maintained. Furthermore, the between cycle (within-trial) variation was not statistically significant. This indicates that the swimmers were able to achieve and maintain maximal UUS velocity within the allotted 4m filming area, and that the variation in the kinematics was stable across both cycles of data collected.

The second aim of the present study was to establish the extent/magnitude of the WS variation apparent in the kinematic variables commonly used to describe and evaluate maximal UUS in skilled swimmers. As there are no other studies which have reported reliability data for UUS, no direct comparisons can be made with the data produced from the protocol used within the present study. However, the levels of CV% reported for three cycles (1.21% - 12.85%) are similar in magnitude to the research of Hunter *et al.* (2004) which examined the reliability of kinematic data in sprint running (three cycle CV% range: 0.6% - 19.9%). Analogous to the research of Hunter *et al.* (2004) the CV% of all the nineteen kinematic variables examined in the present study was found to improve when the number of cycles used to calculate an average score

was increased. Therefore, an increase in the number of cycles of data used to assess and represent a specific variable serves to increase the reliability of the kinematic data making it more likely to represent a *true* value of the kinematics of UUS.

The largest values for WS variability within the kinematic data were found for the shoulder ROM (three cycle CV - 9.17%), wrist JCA (three cycle CV - 12.85%), shoulder JCA (three cycle CV - 8.66%) and shoulder maximum angular velocity (3 cycle CV - 9.68%). The higher levels of variability seen in those variables associated with the movements of the hands and the arms may be accounted for by the swimmers attempting to balance the forces (inertial recoil) produced when kicking. According to previous research (Connaboy *et al.,* 2007a) the hands and arms can act as an inertial damper, helping to maintain an efficient streamline position in the water while also enabling the effective production of a propulsive waveform down the remainder of the body. However, as with all the other variables, the CV% was found to improve when calculated from an increasing number of cycles of data.

The key UUS variables of max *U*, CL and EE_Hz were found to be reliable with CV% values of 1.84%, 1.41% and 3.89% respectively (for three cycles). This improved to 1.30%, 1.00% and 2.75% respectively, when calculated from the average of six cycles. The ROM at the knee was found to have the lowest CV% with 1.21% for three cycles improving to 0.86% for six cycles, signifying that for skilled swimmers the ROM utilised at the knee during maximal UUS performance is maintained within very narrow limits of variability. This is made more interesting when it is considered that the WS variability for the knee JCA is more than twice the

magnitude (three cycle CV – 3.02%, six cycle CV – 2.13%) of the knee ROM, suggesting that the swimmers may be actively trying to maintain the levels of knee ROM by manipulating the coordination of the oscillations of the various joint centres. However, much more research is required to fully explain the factors which interact to produce the coordination observed in the UUS of skilled swimmers.

The third and final aim of the present study was to determine the test-retest reliability of the kinematic data to ascertain the number of cycles/trials necessary to mesure stable levels of performance. While it should be noted that the ICC value at which re-test reliability is deemed to be good (ICC>0.75) is an arbitrary value (Portney and Watkins, 2000). James *et al.* (2007) suggest that the ICC is a more objective means of assessing the number of trials necessary to determine stability of performance than other measures (i.e. sequential averaging) as it involves fewer arbitrary decisions to assess performance stability.

Maximum ICC values were high for all the kinematic measures of UUS performance, ranging from 0.952 for knee JCA up to 0.996 for max *U* for the total thirty cycles recorded. The initial interpretation of the results of the ICC analysis suggests that several cycles (mean 9.47 ± 5.63) of kinematic data are required before the maximum ICC values are achieved for all nineteen kinematic variables. The ICC analyses demonstrate that the test-retest reliability (stability) of maximal UUS is strong for the majority of the kinematic variables measured. All except knee JCA achieved an ICC value of 0.95 within six cycles, and with the majority (68%) achieving an ICC of 0.95 within three cycles. With further iterations of the repeated ICC calculations,

diminishing returns were observed in the increases in the ICC value, hence the relatively high number of cycles required to achieve the maximum ICC values (for thirty cycles), compared to the numbers required to achieve the 0.95 ICC level (mean 3.57 ± 2.09 cycles). Nevertheless, the ICC data should not be considered in isolation. Within-subject variability data should also be taken into account when making decisions regarding the minimum number of cycles required to accurately represent the kinematics of UUS.

By considering the magnitude of WS variation in the selection of the number of cycles required to ensure a reliable assessment of each of the kinematic variables, it provides a measure of the accuracy with which any future changes in the kinematics of UUS can be monitored. Furthermore, the results of ICC analysis should not be considered in isolation when determining the reliability of kinematic variables as they can be adversely influenced by the homogeneity of the sample tested, greatly effecting any interpretation of reliability (Hopkins, 2000; Atkinson and Neville, 1998).

A pragmatic approach to the selection of the number of cycles used to represent the kinematic data needs to be adopted, balancing the need for ensuring high test-retest reliability and acceptable levels of within subject variation with the practical, economic and logistical concerns of collecting repeated cycles of data. As is demonstrated within the present study, by increasing the number of cycles used to calculate a mean value to represent a subject's UUS performance shows an increase in the levels of test-retest reliability and provides increasingly more accurate

representations of the swimmers' performance (lower values of CV). Therefore, given the diminishing returns witnessed in the improvement in the %CV data beyond six cycles and the achievement of a 0.95 ICC values for all but Knee JCA at six cycles it would seem reasonable to conclude that six cycles can be used to accurately represent the kinematics of skilled swimmers UUS performance. Using six cycles, all the kinematic variables demonstrated good levels of reliability as signified by the low WS variation (six cycles – CV range: 0.86% – 8.92%) and high test-retest correlations (six cycles – ICC range: 0.811 – 0.996). Although, as Atkinson and Nevill (1998) suggested, the extent of a variable's reliability is dependent on its intended use, and subsequently a researcher must determine whether it is sufficiently reliable to measure the smallest worthwhile change in an athletes' performance.

3.5 Conclusion

The findings of the present study clearly indicate the requirement for a familiarisation session prior to undertaking an assessment of UUS to ensure reliable data. Additionally, the determination of the number of cycles required to provide accurate and reliable data has shown that an average of ten cycles are required to achieve maximum ICC values (from all thirty cycles) while and average of only four cycles are required to achieve an ICC value of 0.95. However, it should be recognised that when making the decision of how many cycles of data to use to accurately represent a kinematic variable, the data from the ICC analysis should not be viewed in isolation. Consideration of the WS variation is also necessary as having smaller TE/CV% values enables a more precise assessment of worthwhile changes in a variable. The changes in CV% data with the increase in the number of cycles used in the

calculation of CV%, clearly show improved levels of reliability with greater number of cycles of data. However, the improvement in CV% seen with the number of cycles greater than six provided diminishing returns, with less improvement in CV% with each additional cycle of data included in the calculation. Therefore, researchers and applied sports scientist need to consider the practical aspects of collecting large numbers of cycles of data balanced against the requirement to ensure a sufficiently reliable and accurate measurements of the kinematic variables commonly assessed in UUS.

Chapter 4

Study 2:

Identification of key kinematic measures of performance and coordination for maximal underwater undulatory swimming in skilled age-group swimmers

4.1 Introduction

The optimisation of UUS, employed during the underwater phase of the starts and turns of three of the four competitive strokes, is vital to ensure the best possible transition from the glide phase, following entry from a dive or push off from the wall, to full-stroke swimming. According to Mason and Cosser (2000) the production of an effective underwater kicking action is a fundamental factor with respect to the optimisation of start and turn performance. However, despite this integral role in start and turn performance, there is a relative dearth of quantitative research undertaken to specifically identify the key factors involved in the production of a UUS action to maximise swimming velocity.

It has been recognised that UUS is comparable to an undulatory form of locomotion more commonly associated with aquatic animals (Ungerechts, 1987, 1984, 1982; Sanders *et al.,* 1995; Connaboy *et al.,* 2009). An undulatory form of locomotion is accomplished through the production of a propulsive force, generated by a process of wave-like motion passing caudally along the swimming body. A propulsive force is produced if the velocity of the wave travelling along the body exceeds the forward velocity of the swimming body (Sanders *et al.,* 1995).

The factors associated with the production, coordination and control of the propulsive waveform have long been the focus of a great deal of research in marine animals (Gray, 1933; Lighthill, 1975; Blake, 1983; Fish, 1984; McHenry *et al.,* 1995) and more recently in humans (Sanders *et al.,* 1995; Connaboy *et al.,* 2007a,

2007b; Loebbecke e*t al.,* 2009a, 2009b; Hochstein & Blickhan, 2011; Hochstein *et al.,* 2012).

Ungerechts (1984) highlighted that an exceptional feature of swimmers (animal and human) employing an undulatory form of locomotion in an aquatic environment is that the body motions simultaneously provide the propulsive forces and determine the active drag experienced in one unified motion. While the cycle frequency of the end-effector (EE_Hz) adopted has been shown consistently to be a strong predictor of UUS performance (Bainbridge, 1958; Hunter and Zweifel, 1971; Fish, 1984; Long *et al.*, 1994), EE_Hz alone cannot fully explain all the variations apparent in max *U* between performers. Consequently, the relationship between EE_Hz and max *U* is not simply governed by the EE_Hz selected, but also the coordination of the body movements in order to generate that EE_Hz for the production of max *U* (Taneda, 1978; Tomakaru and Dimotakis, 1991; Anderson *et al.,* 1998). Therefore, coordination of cyclical actions ultimately dictates the efficacy of the EE_Hz employed. Accordingly, with regard to the production of a maximal swimming velocity, it would appear necessary to consider not only the relationship between EE_Hz and swimming velocity, but also the interrelationships of the inter and intra-limb coordination occurring at 'optimal' EE_Hz.

While the relationship between EE_Hz, CL and movement velocity is well documented and empirically verified as Velocity = EE_Hz × CL (Craig & Pendergrast, 1979), this does not provide sufficient information to identify and understand the relative importance of other kinematic variables commonly measured

in the execution and analysis of max *U* performance. The variables most commonly utilised when analysing UUS include: joint centre amplitudes (Connaboy *et al.,* 2007a, 2007b; Von Loebbecke *et al.,* 2009; Connaboy *et al.,* 2010; Elipot *et al.,* 2010; Cohen *et al.,* 2012) joint angles, ranges of motion and angular velocities (Arellano *et al.,* 2002; Connaboy *et al.,* 2010; Elipot, *et al.,* 2010), propulsive wave velocities (Sanders, 1995; Gavilan *et al.,* 2006; Connaboy *et al.,* 2007a; Hochstein & Blickhan, 2011) and AoA (Elipot, *et al.,* 2010; Connaboy *et al.,* 2010).

Given the increase in the number of research studies examining UUS performance, and with the recent interest in the use of intra-limb kinematic measures of UUS coordination to understand UUS (Elipot, *et al.,* 2010), further research is required to understand the relative importance of each of these kinematic variables with regard to maximising max *U*. Additionally, research is required to determine which coordination variable(s) can be effectively employed as an order parameter to further examine the stability and variability of the UUS system dynamics when perturbed with the manipulation of a specific control parameter.

The purpose of this study was to identify key kinematic measures of performance and coordination for maximal undulatory underwater swimming in skilled age-group swimmers. To this end two specific aims were addressed: (1) to examine which kinematic variables and measures of coordination provide the best predictive models for (a) EE_Hz (b) CL, and ultimately (c) max *U*; to enable a better understanding of the determinants of max *U* in skilled age group swimmers and (2) establish a

rationale for which measure(s) of coordination could be used as an order parameter to enable an examination of the UUS system dynamics.

4.2 Method

4.2.1 Participants

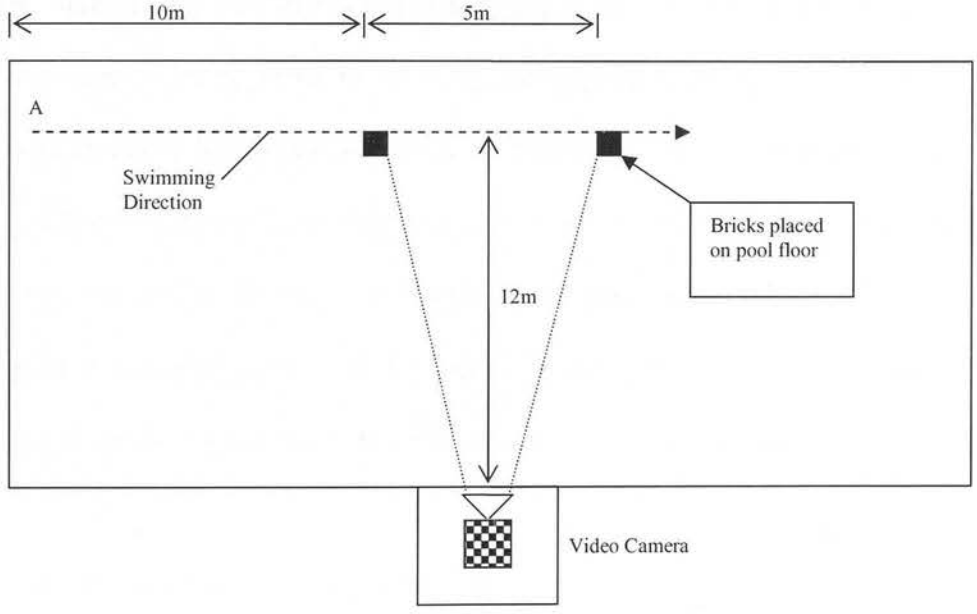
A mixed gender group of seventeen (eight male and nine female) National age-group competitive swimmers (Mean ± SD: Age 16.96 ± 1.36 years, Height 171.26 ± 9.41 cm, Mass 63.28 ± 11.45 kg) from the '*Elite*' squad of a local swimming club participated in this study. Participants were selected on the basis that they had a minimum of five years competitive swimming experience (mean 6.90 ± 1.86 years), had competed in a national age-group championship final and were a member of the club's elite training squad. This would have enabled them to achieve a level of competence which could be considered 'skilled' in UUS. Prior to undertaking the study, ethical approval was granted from the University of Edinburgh Ethics Committee. Informed consent (Appendix 3 and 4) to participate in the study was obtained from each of the participants, in accordance with the regulations and procedures set out by the University of Edinburgh Ethics Committee. No payments were made for the subjects' participation.

4.2.2 Experimental protocol

Seven days prior to data collection, participants performed eight trials of the max U experimental protocol to familiarise themselves with the requirements of the protocol, and to minimise any potential learning effects on the reliability of the data (Study 1). The experimental protocol consisted of each swimmer performing a series

of three maximum effort UUS trials (2 cycles captured per trial), capturing a total of six cycles of UUS data. Six UUS cycles were collected to ensure that the kinematic data would provide a representative and reliable account of the UUS kinematics, as determined in Study 1. Prior to undertaking the three trials a standardised (20 minute) warm-up was conducted to minimise warm-up effects on subsequent performance.

Figure 4.1 Experimental setup; Pool layout



Each trial consisted of the swimmer starting from point A (see Figure 4.1) at the end of the pool, pushing off the wall and swimming underwater using a dolphin leg kick with their arms out-stretched in front of them (see Figure 2.2). The participants attempted to swim as fast as they could, employing a preferred (self-selected) kicking frequency in order to maximise swimming velocity as they swam through the filming area.

The distance from the wall to the start of the filming area (10 m) was sufficient to ensure that the velocity of the swimmer produced from the push off from the wall had no effect on the maximal velocity attained while swimming through the testing area (Arelleno *et al.,* 2002). In addition, the participants were instructed to use the push off from the wall to enable them to achieve the correct orientation (with respect to the camera) and depth (between 0.8 and 1.2 m below the surface of the water), rather than as a means to maximise velocity.

The participants were instructed to accelerate over the first 10 m to attain maximum swimming velocity prior to entering the beginning of the filming area, and to maintain that velocity throughout the entire filming area. No instructions were given regarding the cycle frequency that should be employed, except that participants should attempt to maximise swimming velocity on each of the trials. Participants repeated the procedure a total of three times, with a minimum five-minute rest interval between trials to allow a full recovery and minimise the effects of fatigue.

4.2.3 Data collection and processing

Participant preparation

Participants were marked at the joint centres of the shoulder, hip, knee, ankle and 5th metatarsal phalangeal joint (5th MPJ) of the foot on the right side of the body with a 3cm diameter circle of black oil-based body paint. The length of each participant's thigh was measured (on land) and recorded. This known length was used as the scale factor for each frame of their video data (Clothier *et al.,* 2004).

Filming, Digitising and Data Processing procedures

The filming, digitising and data processing procedures were identical to those detailed in section 3.2.3 (Chapter 3)

4.2.4 Data analysis

A total of nineteen kinematic variables already commonly identified as important in UUS (see chapter 2.3) were calculated for each kick cycle: (1) max *U*, (2) EE_Hz, (3) CL; joint ranges of motions of (4) shoulder, (5) hip, (6) knee, (7) ankle; maximum angular velocities of (8) shoulder, (9) hip, (10) knee, (11) ankle; vertical joint centre amplitudes of (12) wrist, (13) shoulder, (14) hip, (15) knee, (16) ankle, (17) 5^{th} MPJ; (18) maximum angle of attack, and (19) the mean absolute AoA of the end-effector (see chapter 3 for calculations of kinematic variables).

Eleven discrete measures of coordination were determined: Propulsive wave speed (20) shoulder-hip, (21) hip-knee, (22) knee-ankle, (23) ankle-5^{th} MPJ; mean absolute relative phase (MARP) for (24) Trunk v Thigh segment angle, (25) Thigh v Shank segment angle, (26) Shank v Foot segment angle, (27) Trunk v Shank segment angle, (28) Trunk v Foot segment angle, (29) Thigh v Foot segment angle, (30) Heave v Pitch angle of the end-effector.

A further series of seven continuous measures of inter and intra-limb coordination were also calculated to provide additional spatiotemporal data to examine the relative importance of the kinematic variables and coordination measures: Continuous relative phase (CRP) for (35) Trunk v Thigh, (36) Thigh v Shank, (37) Shank v Foot,

(38) Trunk v Shank, (39) Trunk v Foot, and (40) Thigh v Foot segments. In addition, CRP was calculated for (41) Heave v Pitch angle of the end effector.

The discrete and continuous measures of (inter/intra-limb) coordination were included to capture the complexities of the swimmers' movement patterns. An undulatory mode of swimming occurs as the product of a series of temporally sequenced oscillations which occur along the length (or a section) of the body. The sequence of the oscillations are such that they create 'bends' which pass along the length of the body generating an undulatory wave, transferring momentum to the surrounding water producing a propulsive force (McHenry *et al.*, 1995). In order that forward swimming motion occurs it is necessary that the speed of the wave exceeds the forward swimming velocity.

The inclusion of a measure of propulsive wave velocity was necessary to understand the controlling mechanisms in the production of an optimal cycle frequency for maximal swimming velocity (Fish, 1984). Ascertaining the relationship between average swimming velocity and cycle frequency is redundant if the factors contributing to the production of both these variables are not understood. A measure of propulsive wave velocity provides insight into how the swimmer produces the propulsive force necessary for forward propulsion during the kicking action, and how a skilled swimmer attempts to solve the movement equation within the confines of the environmental (hydrodynamic) constraints. According to previous research (Fish, 1984; Webb, 1978; Lighthill, 1970), if propulsive wave velocity is large relative to max U then unnecessary energy is being expended.

To provide a more detailed account of the relationships apparent between the coupled limbs or joints, measures of continuous relative phase (CRP) were included. Continuous relative phase has been used as a measure of coordination between two segments or joints in many studies of locomotion (Hamill *et al.,* 1999; Schloz and Kelso, 1989; Kelso *et al.,* 1986; Haken *et al.,* 1985). According to Stergiou *et al.* (2001), CRP depicts the coordination between two interacting segments/limbs throughout the entire movement sequence indicating how the two segments/limbs are coupled. They have been used to provide indications as to any changes in the association and relationships between segments and insight into the control mechanisms of a particular movement (Winstein and Garfinkel, 1989; Buzzi *et al.,* 2003). Therefore, an assessment of the variation of the CRP can provide information as to how consistently swimmers reproduce a coordination pattern and which points in the cyclical action are more highly constrained / controlled at their preferred cycle frequency.

Employing a measure of CRP also has advantages as it provides information regarding both the spatial and temporal aspects of the relative motion of two coupled oscillators (Haddad *et al.,* 1999). Furthermore, CRP is believed to be sensitive enough to allow a measurement of the effects of factors such as learning or changes in environmental conditions to be assessed for a movement coordination pattern (Burgess-Limerick *et al.,* 1993). To enable effective comparison between participants all the continuous data were normalised to 101 data points for each cycle.

4.2.5 Calculation of discrete and continuous measures of coordination.

Propulsive wave speed (m.s.$^{-1}$).

Propulsive wave speed was calculated between each of the anatomical markers, and along the length of the swimmers body (shoulder to 5th MPJ). The calculation methods adopted by Sanders *et al.* (1995) and Sanders *et al.* (1998) were utilised in the present study. This required vertical displacement data of the shoulder, hip, knee, ankle and 5th MPJ to be analysed using the discrete Fourier transform. Prior to entering the vertical position data of each of the reference points into the Fourier transform the data were demeaned and detrended so that the data oscillated around zero, allowing for the direct comparison of the harmonics of the individual points along the body.

The output of the Fourier transform comprised the cosine and sine coefficients of the fundamental frequency and its harmonics. The Fourier coefficients were calculated using the following equation:

$$\mathbf{A}_n = \sum_{r=-n}^{n-1} \mathbf{S}_r \times \mathbf{Cos}\left(\frac{\mathbf{2}\ \pi\ m\ \mathbf{r}}{N}\right)$$

and

$$\mathbf{B}_n = \sum_{r=-n}^{n-1} \mathbf{S}_r \times \mathbf{Sin}\left(\frac{\mathbf{2}\ \pi\ m\ \mathbf{r}}{N}\right) \qquad (7)$$

where A_n is the amplitude of the cosine function, B_n is the amplitude of the sine function, N is the number of data points, S_r is the rth sample value, π = 3.1415927, r is the number of the sample, and m is the harmonic number.

The amplitude of each frequency for every harmonic was calculated as:

$$C_n = (A_n^2 + B_n^2)^{0.5} \quad (8)$$

where A_n and B_n are cosine and sine coefficients respectively, for the nth Fourier frequency (harmonic).

The phase angle was calculated by:

$$\theta = \tan^{-1}(B_n / A_n) \quad (9)$$

The contribution of each frequency to the mean square value, or average power, of the signal was given by:

$$2\sigma_x^2 \quad (10)$$

Once the phase angle of the respective harmonics had been calculated for all the points along the body, the velocity of the waves between the adjacent points were calculated, to verify whether the undulatory body wave was passing along (in a cephalo-caudal direction) the body faster than the swimmer's forward velocity. The velocity of the wave travelling along the body was determined for the fundamental frequency (Harmonic 1 - H1).

The mean velocity of wave travel was determined for shoulder to hip, hip to knee, knee to ankle, and ankle to the 5th MPJ along the right side of the body, using the relationship:

$$v = d/t, \quad (11)$$

where v is the velocity of the fundamental frequency (H1) travelling along the body, d is the displacement (m) between adjacent points (joint centres), and t is the time taken for the oscillation of the rear most (caudal) of the two adjacent points to achieve the same phase as the preceding more cephalic point. Displacement between adjacent points was regarded as the mean difference in the x values of the two adjacent joint centres throughout the entire period of analysis (one compete kick cycle).

Time was calculated using:

$$t_m = (\theta_m - \theta_{m+1}) \times T/360 \quad (12)$$

Where, θ_m is the phase angle of the mth point and T is the period of the kick cycle. Thus with displacement and time, it was possible to calculate the speed of wave travel over each body segment in $m.s.^{-1}$.

Heave and Pitch Angle

The research of Hertel (1966) and Anderson *et al.* (1998) proposed that the phase relationships between the heave motions and pitch angle oscillations act to determine and control the propulsive performance of the caudal aspects of the swimming body. Anderson *et al.* (1998) suggested that the relative-phase relationship between the heave and pitch of the end-effector is critical to the maximisation of an effective propulsive force and simultaneously the minimisation of active drag. The heaving motions are calculated as the vertical, quasi-sinusoidal motions produced at the end-effectors (ankle joint) during UUS. The pitch angle is calculated as the segment

angle of line between the joint centre of the ankle and the 5th MPJ, relative to the path of the swimmer (Figure 2.2).

Phase Angle

Phase-plane diagrams were constructed with angular displacement (θ) on the horizontal (x) axis and the first derivative, angular velocity (ω) on the vertical (y) axis. Quantification of the phase-plane diagrams was accomplished by means of calculating the phase angle for every point throughout a kick cycle. The phase angle (Φ) was determined to quantify the joint/segment movement behaviour. Following the methods employed by Clark and Phillips (1993) and Kelso *et al.* (1986) the phase-plane trajectories were transformed from a Cartesian system (x,y) to polar coordinates (with a radius and phase angle).

The Φ was calculated[1] as the angle between the right horizontal and a line drawn to a specific data point (θ_i,ω_i) from the origin (0,0). The radius was determined as the length of the unit vector from the origin (0,0) to the same specific data point (θ_i,ω_i). The Φ at each percentile of the kick cycle was then determined using the following equation (Kurz and Stergiou, 2002; Stergiou *et al.*, 2001; Hamill *et al.*, 1999; Li, *et al.*, 1999):

$$\Phi = \tan^{-1} \omega_i(t)/ \theta_i(t) \qquad (13)$$

where, $\omega_i(t)$ is the angular velocity and $\theta_i(t)$ is the angular displacement for the ith point during the kick cycle. Adjustments as angles crossed quadrants (determined

[1] Prior to phase angle calculations data were interpolated to 101 points to represent percentage points of each cycle enabling a direct comparison between cycles.

from the values of ω and θ) were in accordance with the procedures outlined by Hamill *et al.* (1999). As with angle-angle plots, the directional nature of the phase-plane diagrams and the Φ calculations requires that the mean direction of the resultant vector from the phase plane diagram (Φ_{mean}) to be determined with circular statistics (Batschelet, 1981).

The Φ_{mean} was determined for each participant for each cycle[2], trial and session segment angle data using the following procedures,

$$x_{mean} = \frac{1}{n}\sum_{i=1}^{n}\cos\theta_i \tag{14}$$

$$y_{mean} = \frac{1}{n}\sum_{i=1}^{n}\sin\theta_i \tag{15}$$

If $x_{mean} > 0$

$$\Phi_{mean} = \tan^{-1}\left(\frac{y_{mean}}{x_{mean}}\right) \tag{16}$$

If $x_{mean} < 0$

$$\Phi_{mean} = 180 + \tan^{-1}\left(\frac{y_{mean}}{x_{mean}}\right) \tag{17}$$

where, θ is the θ of the i^{th} data point and n is the number of data points.

[2] Only Φ_{mean} for individual cycle data was included in the subsequent ANCOVA models.

Continuous Relative Phase

Continuous Relative Phase (CRP) between respective segments were calculated. In addition, CRP was calculated for Heave v Pitch angle of the end effector. The Φ from the respective displacement-velocity phase-plane diagrams were first calculated for each of the respective segments. The Φ was defined as the angle between the right horizontal and a line drawn to a specific data point (θ_i,ω_i) from the origin (0,0).

Prior to calculating Φ, the phase-portrait values were normalised to the minimum and maximum values found along each axis using the protocol outlined by Li et al. (1999), using the following formula:

$$\text{Horizontal axis (angle)} : \theta_i = \frac{2 \times [\theta_i - \min(\theta_i)]}{\max(\theta_i) - \min(\theta_i)} - 1 \quad (18)$$

The CRP was calculated as the difference between the relative segment angles at each of the 101 data points. The normalisation procedures act to minimise the influence of different segmental movement amplitudes (Li et al., 1999) and allow comparisons of UUS cycles with different temporal structures. Ensemble curves were produced for the individual CRP profiles by determining the mean CRP value at each of the 101 data points from the 6 UUS cycles. The variability in the CRP was displayed as the standard deviation of the 6 trials at each data point.

Mean Absolute Relative Phase Angle.

Mean absolute relative phase (MARP) angle was calculated to provide a discrete measurement of the overall coupling between the segment pairs (McKeon *et al.*,

2009). The MARP angle over a complete kick cycle was calculated using methods outlined in Hamill *et al.* (1999), Heiderscheit, *et al.* (1999) and Stergiou (2004):

$$\text{MARP} = \sum_{i=1}^{N}\left(\frac{|\Phi\text{relative phase}|}{N}\right) \tag{19}$$

4.2.6 Statistical Analysis

All statistical analyses were performed using the Statistical Package for the Social Sciences (PASW Statistics 18.0, SPSS Inc., Chicago, IL). Pearson product–moment correlations were carried to examine the relationship between each of the kinematic variables and measures of coordination and the three dependent variables (DVs- 1. max *U*, 2. EE_Hz, 3. CL). The Pearson product–moment correlations were undertaken to establish the type of relationship between the respective kinematic variables / coordination measures and DVs, as a linear relationship is a prerequisite for the ANOVA and ANCOVA statistical models.

Before ascertaining the best predictive models for each of the three DVs the normality of the data distribution for each DV was determined using the Kolmogorov-Smirnov test for normality. Prior to including kinematic variables / coordination measures into the separate ANCOVA models, separate one-way ANOVAs were performed to determine any significant differences in the each of the kinematic variables / coordination measures by Gender, to ensure that the assumptions of the ANCOVA model are not violated. Any kinematic variables /

coordination measures which were found to be significantly different by Gender were excluded from any further analysis in the ANCOVA models (Field, 2000).

Backward elimination Analysis of Covariance (BE ANCOVA) models were utilised to ascertain which individual kinematic variable / coordination measure, or collection of kinematic variables / coordination measures provided the best predictive models for each of the three DVs, using the methods outlined in Draper and Smith, (1998). The BE ANCOVA analysis model was selected because it has the capacity to fit a fixed between-subject indicator variable (n=17) and enables the estimation of a within-subject source of variation (6 cycles) as part of the error structure (Nevill *et al.* 2011; Brown *et al.,* 2011). This enables the ANCOVA analysis to partition the two sources of variation (between and within subject variation). Therefore, participant number was used as a fixed factor to ensure the analysis allowed for individual differences in the respective DVs.

The value of using a BE ANCOVA model in this way, over a multiple regression model, is that it enables a greater number of trials (n=6) from the same participant to be entered into the model rather than a mean value. As the various sources of variation (between subject and within subject) can be partitioned, their relative influence on the final model can be determined. This allows a more comprehensive analysis of the data to take place as the ratio of variables to data points is not a limiting factor for the ANCOVA model, whereas a (similar) stepwise multiple regression model requires a minimum of 20 subject data points for each additional variable entered into the statistical model (Hair *et al.,* 1998).

Given the known relationship between velocity, cycle frequency and cycle length (Velocity = EE_Hz x CL) and understanding that the inclusion of these two variables alone (EE_Hz and CL) into a statistical model designed to determine the relationship between kinematic variables and the production of max *U* would explain the entire variance in Velocity (r^2 value =1.00), separate BE ANCOVA models, were used to determine which of the kinematic variables and measures of coordination were best able to explain the variation for each the three DVs from all the 102 data cycles (17 participants × 3 trials × 2 cycles).

Through a process of backward elimination a parsimonious model of the determinants of each of the respective DVs was produced. The parsimonious model was achieved by a process of iteration, starting with the saturated model containing all the covariates, the least important covariate (as denoted by the largest *p*-value) was withdrawn from the model and the ANCOVA statistic recalculated. This process was repeated until all the remaining 'predictor' variables provided a significant contribution to the final parsimonious model (Bridgewater and Sharpe, 1998; Nevill *et al.* 2010; Nevill *et al.* 2011). In all cases, alpha values of less than 0.05 were accepted as being significant. Effect size statistics were determined for each variable contained within the final parsimonious models using partial-Eta^2 (η_p^2) (Brown *et al.*, 2011; Cohen, 1988).

Both EE_Hz and CL were excluded from the final model (DV= max *U*) and the results from the initial series of parsimonious ANCOVA models for EE-Hz and CL

were used to determine which variables would be entered into the initial 'saturated' ANCOVA model to analyse max *U*.

4.3 Results

The one-way ANOVA identified statistically significant differences by gender in nine of the thirty discrete kinematic variables and measures of coordination analysed (Table 4.1 and 4.2). These nine variables were excluded from any further analysis in the BE ANCOVA models. Mean values for the kinematic variables and measures of coordination are shown in tables 4.1 and 4.2 respectively. Those kinematic variables and coordination measures identified as statistically different by gender are included in Table 4.1, showing that the female age-group swimmers had a higher wrist (+15.2 mm), ankle (+35.5 mm) and 5th MPJ (+34.6 mm) amplitude. The females also had both a larger ROM (+5.48°) and a higher angular velocity (+53.11°·s^{-1}) at the ankle.

The discrete coordination data (Table 4.2) also shows females presenting statistically significant, higher values in Hip–Knee wave (+0.302 m.s^{-1}), MARP Foot v Shank (+2.51°) and lower values in MARP for Shank v Thigh (-5.26°) and Shank v Trunk (-5.24°) than their male counterparts.

Gender differences were also apparent in the correlation data for both kinematic variables (Table 4.3) and coordination measures (Table 4.4). These tables (4.3 and 4.4) show the Pearson product-moment correlations (*r*) and the statistical significance (*p*-value) for the respective kinematic variables and measures of

coordination in relation to the EE_Hz, CL and max *U* for female, male and pooled data (All).

Table 4.1 Mean (±SD) kinematic variables for female, male and all age- group swimmers combined.

	Female			Male			All		
Kinematic Variable	Mean		SD	Mean		SD	Mean		SD
EE_Hz (hz)	2.11	±	0.28	2.15	±	0.17	2.13	±	0.23
Max *U* (m.s.$^{-1}$)	1.196	±	0.116	1.200	±	0.153	1.198	±	0.134
Wrist Amplitude (mm)*	84.20	±	38.24	69.00	±	24.80	77.05	±	33.34
Shoulder Amplitude (mm)	74.90	±	19.59	76.13	±	15.59	75.48	±	17.74
Hip Amplitude (mm)	133.48	±	28.58	123.68	±	24.22	128.87	±	26.94
Knee Amplitude (mm)	272.38	±	43.07	261.52	±	41.74	267.27	±	42.59
Ankle Amplitude (mm)**	472.45	±	52.20	436.95	±	63.17	455.75	±	60.03
5th MPJ Amplitude (mm)*	623.76	±	66.86	589.11	±	71.49	607.46	±	70.90
Cycle Length (mm)	573.73	±	65.60	561.63	±	72.43	568.03	±	68.82
Max Shoulder Velocity ($^{\circ}$·s^{-1})	179.47	±	30.73	181.34	±	44.72	180.35	±	37.78
Max Hip Angle Velocity ($^{\circ}$·s^{-1})	302.64	±	65.77	297.45	±	49.94	300.20	±	58.63
Max Knee Angle Velocity ($^{\circ}$·s^{-1})	703.38	±	91.44	701.89	±	73.16	702.68	±	82.94
Max Ankle Angle Velocity ($^{\circ}$·s^{-1})*	511.07	±	121.24	457.96	±	95.38	486.08	±	112.50
Shoulder ROM ($^{\circ}$)	27.99	±	5.67	28.57	±	6.88	28.26	±	6.24
Hip ROM ($^{\circ}$)	47.59	±	10.14	49.04	±	7.84	48.27	±	9.11
Knee ROM ($^{\circ}$)	89.12	±	7.40	90.17	±	6.36	89.61	±	6.92
Ankle ROM ($^{\circ}$)*	56.40	±	7.90	50.92	±	7.43	53.82	±	8.12
Max AoA ($^{\circ}$)	75.99	±	7.58	77.83	±	7.52	76.85	±	7.57
Mean Absolute AoA ($^{\circ}$)	43.87	±	2.00	43.83	±	2.21	43.85	±	2.09

Statistically significant difference between males and females *p<0.05, **p<0.01

When the data were separated by gender, a number of kinematic variables indicated large disparities in their respective correlations with the DVs (Table 4.3). Females showed a strong negative relationship between EE_Hz and shoulder amplitude (r = -0.767, p<0.01) compared to the moderate negative relationship (r = -0.308, p<0.05) for males. Females showed a strong negative relationship between CL and maximal ankle angle velocity (r = -0.602, p<0.01) compared to the moderate negative value (r = -0.152, p=0.302) for males.

Table 4.2 **Mean (±SD) measures of coordination for female, male and all age-group swimmers combined.**

	Female			Male			All		
Measures of Coordination	Mean		SD	Mean		SD	Mean		SD
Shoulder- Hip Wave (m.s.-^{1})	-2.369	±	1.271	-2.654	±	0.305	-2.503	±	0.955
Hip - Knee Wave (m.s.-^{1})*	-3.626	±	0.618	-3.324	±	0.586	-3.484	±	0.619
Knee-Ankle Wave (m.s.-^{1})	-2.983	±	0.453	-3.033	±	0.267	-3.007	±	0.376
Ankle-Foot Wave (m.s.-^{1})	-4.567	±	0.832	-4.455	±	0.644	-4.515	±	0.748
MARP Foot v Shank (°)*	29.95	±	6.07	27.44	±	3.67	28.77	±	5.19
MARP Foot v Thigh (°)	121.69	±	12.88	124.44	±	7.80	122.99	±	10.78
MARP Foot v Trunk (°)	184.21	±	33.23	187.27	±	31.42	185.65	±	32.10
MARP Shank v Thigh (°)**	91.76	±	8.34	97.02	±	6.52	94.24	±	7.92
MARP Shank v Trunk (°)*	173.17	±	10.42	178.41	±	10.77	175.64	±	10.80
MARP Thigh v Trunk (°)	92.66	±	12.25	98.56	±	11.07	95.44	±	12.49
MARP Heave v Pitch angle (°)	117.40	±	4.53	118.91	±	4.41	118.11	±	4.49

Statistically significant difference between males and females *p<0.05, **p<0.01

In addition, females had strong positive relationships between: EE_Hz and maximal ankle velocity (r = 0.657, p<0.01 compared to r = 0.147, p=0.322 for males), max U and maximal hip velocity (r = 0.687, p<0.01 compared to r = 0.009, p=0.953 for males), max U and max AoA (r = 0.807, p<0.01 compared to r =-0.186, p=0.207 for males).

Conversely, males had a strong relationship between EE_Hz and hip ROM (r = -0.613, p<0.01 compared to r = -0.116, p=0.405 for females) and EE_Hz and knee ROM (r = -0.608, p<0.01 compared to r = -0.148, p=0.732 for females). Males also had strong relationships between CL and max U (r = 0.815, p<0.01 compared to r = 0.103, p=0.457 for females), and for CL and mean absolute AoA (r = -0.554, p<0.01 compared to r = -0.134, p=0.333 for females).

The instances where the pooled data from both males and female had a strong relationship ($r > 0.5$) between the kinematic variables are EE_Hz and: wrist amplitude ($r = -0.589$, $p<0.01$); shoulder amplitude ($r = -0.620$, $p<0.01$); CL ($r = -0.563$, $p<0.01$); maximal knee angle velocity ($r = -0.567$, $p<0.01$). The largest correlation for CL and the kinematic variables were for: EE_Hz($r = -0.563$, $p<0.01$); shoulder amplitude ($r = 0.620$, $p<0.01$); hip amplitude ($r = 0.629$, $p<0.01$); ankle amplitude ($r = 0.565$, $p<0.01$); 5^{th} MPJ ($r = 0.594$, $p<0.01$). Only one kinematic variable produced an r-value in excess of 0.5 (maximal knee angle velocity, $r = 0.639$, $p<0.01$).

The strongest identified relationships by gender were; max AoA and max U ($r = 0.807$, $p<0.01$) for females and CL and max U ($r = 0.815$, $p<0.01$) for males. When the data were pooled the highest correlation values was between maximal knee angle velocity and max U ($r = 0.639$, $p<0.01$).

Table 4.3 **Pearson's Correlation Coefficient: Kinematic Variables Relationships with End-Effector Cycle Frequency, Cycle Length & Max *U***

	EE_Hz						CL						Max *U*					
	Female		Male		All		Female		Male		All		Female		Male		All	
Kinematic Variable	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
EE_Hz (hz)							-0.731	**	-0.335	0.020*	-0.563	**	0.590	**	0.271	0.062	0.426	**
Max *U* (m.s.-1)	0.590	**	0.271	0.062	0.426	**	0.103	0.457	0.815	**	0.499	**						
Wrist Amplitude (mm)	-0.596	**	-0.566	**	-0.589	**	0.311	0.022*	0.352	0.014*	0.327	0.001**	-0.550	**	0.011	0.940	-0.285	0.004**
Shoulder Amplitude (mm)	-0.767	**	-0.308	0.033*	-0.620	**	0.653	**	0.611	**	0.620	**	-0.349	0.010**	0.446	0.002**	0.034	0.735
Hip Amplitude (mm)	-0.406	**	-0.426	0.003**	-0.414	**	0.664	**	0.592	**	0.629	**	0.225	0.102	0.344	0.017*	0.270	0.006**
Knee Amplitude (mm)	-0.094	0.498	-0.527	**	-0.244	0.014*	0.514	**	0.369	0.010*	0.449	**	0.529	**	0.043	0.769	0.263	0.008**
Ankle Amplitude (mm)	-0.298	0.028*	-0.524	**	-0.372	**	0.542	**	0.589	**	0.565	**	0.266	0.052	0.276	0.058	0.255	0.10**
5th MPJ Amplitude (mm)	-0.270	0.48*	-0.447	0.001**	-0.330	0.001**	0.548	**	0.635	**	0.594	**	0.316	0.020*	0.377	0.008**	0.333	0.001**
Cycle Length (mm)	-0.731	**	-0.335	0.020*	-0.563	**							0.103	0.457	0.815	**	0.499	**
Max ShoulderAngle Velocity(°s^{-1})	-0.020	0.885	-0.106	0.474	-0.051	0.614	-0.026	0.851	0.256	0.079	0.136	0.173	-0.007	0.959	0.194	0.187	0.120	0.231
Max Hip Angle Velocity (°s^{-1})	0.301	0.027*	-0.196	0.182	0.152	0.127	0.203	0.141	0.126	0.393	0.170	0.087	0.687	**	0.009	0.953	0.353	**
Max Knee Angle Velocity (°s^{-1})	0.557	**	0.613	**	0.567	**	-0.075	0.591	0.165	0.261	0.031	0.757	0.757	**	0.556	**	0.639	**
Max Ankle Angle Velocity (°s^{-1})	0.657	**	0.146	0.322	0.407	**	-0.602	**	-0.152	0.302	-0.367	**	0.243	0.077	-0.088	0.551	0.075	0.452
Shoulder ROM (°)	-0.167	0.227	-0.372	0.009**	-0.230	0.020*	0.095	0.492	0.448	0.001**	0.281	0.004**	-0.059	0.673	0.255	0.124	0.108	0.278
Hip ROM (°)	-0.116	0.405	-0.613	**	-0.252	0.011*	0.529	**	0.478	0.001**	0.489	**	0.489	0.001**	0.109	0.460	0.298	0.002**
Knee ROM (°)	-0.048	0.732	-0.608	**	-0.214	0.030*	0.366	0.007**	0.232	0.112	0.294	0.003**	0.443	0.001**	-0.137	0.355	0.149	0.134
Ankle ROM (°)	-0.037	0.790	-0.386	0.007**	-0.168	0.092	-0.253	0.064	0.205	0.162	-0.002	0.987	-0.403	0.003**	-0.030	0.840	0.198	0.047*
Max AoA (°))	0.501	**	0.420	0.003**	0.465	**	0.050	0.722	-0.440	0.002**	-0.200	0.044*	0.807	**	-0.186	0.207	0.270	0.006**
Mean Absolute AoA (°)	0.272	0.047*	0.333	0.021*	0.281	0.004**	-0.134	0.333	-0.554	**	-0.350	**	0.310	0.023*	-0.358	0.012*	-0.067	0.504

* = p<0.05; **= p<0.01

Table 4.4 shows the statistical relationship (Pearson product-moment correlations) between each of the discrete measures of coordination and the three DVs. Similar differences to those apparent between genders observed in the performance data (Table 4.3) also occur in the relationships within the coordination data. Females showed a strong positive relationship between EE_Hz and MARP Foot v Thigh (r = 0.607, p<0.01) compared to the weak positive relationship (r = 0.110, p= 0.609) for males. Females also demonstrated a strong positive relationship between EE_Hz and MARP Shank v Thigh (r = 0.616, p<0.01) compared to the moderate positive value (r = 0.308, p=0.067) for males; and for EE_Hz and MARP Thigh v Trunk, were females had a strong positive relationship (r = 0.507, p<0.01) compared to a weak negative correlation for males (r = -0.009, p=0.967).

For CL, females showed a strong positive relationship with Hip-Knee wave (r = 0.588, p<0.01) and MARP Heave v Pitch angle (r = 0.704, p<0.01) and a strong negative correlation with MARP Foot v Shank (r = -0.812, p< 0.01) and MARP Foot v Thigh (r = -0.750, p<0.01) compared to weak positive (Hip-Knee wave r = 0.100, p<0.501; MARP Foot v Shank r = -0.199, p=0.352) and weak negative relationships (MARP Heave v Pitch angle r = -0.182, p=0.395; MARP Foot v Thigh r = -0.295, p=0.162) for males. Conversely, males showed strong positive relationships between CL and MARP Thigh v Trunk (r = 0.520, p<0.01) compared to females' weak negative MARP Thigh v Trunk (r = -0.151, p=0.452) correlations.

Table 4.4 Pearson's Correlation Coefficient: Measures of Coordination Relationships with End-Effector Cycle Frequency, Cycle Length & Max *U*

	EE_Hz						CL						Max *U*					
	Female		Male		All		Female		Male		All		Female		Male		All	
Coordination Variable	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Shoulder_Hip_Wave (m.s.-1)	-0.042	0.766	-0.538	**	-0.104	0.297	-0.031	0.823	-0.088	0.551	-0.021	0.832	-0.145	0.296	-0.422	0.003**	-0.161	0.105
Hip_Knee_Wave (m.s.-1)	-0.502	**	-0.594	**	-0.485	**	0.588	**	0.100	0.501	0.318	0.001**	-0.056	0.685	-0.259	0.076	-0.152	0.127
Knee_Ankle_Wave (m.s.-1)	-0.822	**	-0.550	**	-0.758	**	0.382	.004**	-0.326	0.024*	0.122	0.222	-0.745	**	-0.670	**	-0.661	**
Ankle_Foot_Wave (m.s.-1)	-0.599	**	-0.604	**	-0.588	**	0.197	0.154	-0.040	0.789	0.086	0.390	-0.686	**	-0.413	0.004**	-0.534	**
MARP Foot_Shank (˚)	-0.441	0.021*	-0.437	0.033*	0.206	0.147	-0.812	**	0.199	0.352	-0.375	0.007**	-0.334	0.089	-0.060	0.780	-0.201	0.156
MARP Foot_Thigh (˚)	0.607	0.001**	0.110	0.609	0.491	**	-0.750	**	-0.295	0.162	-0.555	**	-0.010	0.961	-0.241	0.256	-0.096	0.502
MARP Foot_Trunk (˚)	-0.372	0.096	-0.077	0.719	-0.235	0.098	-0.031	0.879	0.474	0.019*	0.210	0.139	-0.427	0.026*	0.440	0.032*	0.028	0.844
MARP Shank_Thigh (˚)	0.616	**	0.380	0.067	0.533	**	-0.564	0.002**	-0.466	0.022*	-0.508	**	0.231	0.247	-0.255	0.230	0.003	0.985
MARP Shank_Trunk (˚)	0.259	0.192	-0.139	0.517	0.128	0.370	-0.390	0.044*	0.301	0.142	-0.051	0.722	-0.014	0.943	0.234	0.272	0.120	0.403
MARP Thigh_Trunk (˚)	0.507	0.007**	-0.009	0.967	0.343	0.014*	-0.151	0.452	0.520	0.009**	-0.322	0.021*	0.497	0.008**	-0.536	0.007**	-0.021	0.882
MARP Heave v Pitch angle (˚)	-0.553	0.003**	0.597	0.002**	-0.146	0.308	0.704	**	-0.182	0.395	0.245	0.083	0.022	0.912	0.181	0.398	0.106	0.460

* = p<0.05; **= p<0.01

No large disparities were observed between genders for any of the correlation coefficients for max U and the measures of coordination. For the combined data (males and females pooled), seven measures of coordination were reported as having strong relationships for EE_Hz (knee-ankle wave r = -0.758, p<0.01; ankle-foot wave r = -0.588, p<0.01; MARP Shank v Thigh r = 0.533, p<0.01), CL (MARP Foot v Thigh r = -0.555, p<0.01; MARP Shank v Thigh r = -0.508, p<0.01) and max U (knee-ankle wave r = -0.661, p<0.01; ankle-foot wave r = -0.534, p<0.01).

Finally, the strongest identified relationships by gender were; EE_Hz and knee-ankle wave (r = 0.822, p<0.01) for females and max U and knee-ankle wave (r = -0.670, p<0.01) for males. When the data was pooled the highest correlation value is for EE_Hz and knee-ankle wave (r = -0.758, p<0.01).

Analysis of covariance: Backward elimination models

After removal of the nine variables (five kinematic variables and four measures of coordination) that were found to be statistically different by gender (Table 4.1 and 4.2) and the alternate removal of the other DV's the remaining kinematic variables and measures of coordination were entered as covariates in separate, saturated ANCOVA models for kinematic variables and measures of coordination to determine the best predictive models for EE_Hz and CL. Through a backward elimination, iterative process the separate saturated ANCOVA models were reduced to parsimonious models containing only those covariates which significantly (p<0.05) explained a portion of the variance of the DV (EE_Hz or CL).

Kinematic variables

DV - End-effector cycle frequency (EE_Hz)

Through the iterative process, the initial saturated model containing all the covariates (following the removal of those which were significantly different by gender) was reduced to a parsimonious model containing only six covariates which all contributed to an explanation of the variance of the DV: shoulder amplitude ($p<0.001$; $\eta_p^2 = 0.179$), knee amplitude ($p<0.001$; $\eta_p^2 = 0.160$), max hip angle velocity ($p<0.001$; $\eta_p^2 = 0.169$), max knee angle velocity ($p<0.001$; $\eta_p^2 = 0.194$), mean absolute AoA ($p = 0.011$; $\eta_p^2 = 0.079$), knee ROM ($p = 0.002$; $\eta_p^2 = 0.119$). The fixed factor (Participant) significantly contributed to the model ($p<0.001$; $\eta_p^2 = 0.585$). The r^2 value was 0.901 and the Adj. r^2 value was 0.874.

DV - Cycle length (CL)

For CL the final parsimonious model for performance variables was reduced to five covariates: shoulder amplitude ($p = 0.01$; $\eta_p^2 = 0.080$), knee amplitude ($p<0.001$; $\eta_p^2 = 0.226$), hip amplitude ($p = 0.031$; $\eta_p^2 = 0.057$), max hip velocity ($p<0.001$; $\eta_p^2 = 0.133$), mean absolute AoA ($p<0.001$; $\eta_p^2 = 0.135$). The fixed factor (Participant) significantly contributed to the model ($p<0.001$; $\eta_p^2 = 0.736$). The r^2 value was 0.905 and the Adj. r^2 was 0.880.

Measures of coordination

DV - End-effector cycle frequency (EE_Hz)

The resultant parsimonious model for EE_Hz contained four covariates: shoulder-hip wave ($p<0.001$; $\eta_p^2 = 0.235$), knee-ankle wave ($p<0.001$; $\eta_p^2 = 0.625$), MARP foot v

thigh ($p<0.001$; $\eta_p^2 = 0.193$), MARP Heave v Pitch angle ($p = 0.003$; $\eta_p^2 = 0.107$). The fixed factor (Participant) significantly contributed to the model ($p<0.001$; $\eta_p^2 = 0.751$). The r^2 value was 0.946 and the Adj. r^2 was 0.932.

DV - Cycle length (CL)

Shoulder-hip wave ($p = 0.016$; $\eta_p^2 = 0.070$), knee-ankle wave ($p<0.001$; $\eta_p^2 = 0.290$), MARP foot v thigh ($p<0.001$; $\eta_p^2 = 0.187$), MARP Heave v Pitch angle ($p = 0.027$; $\eta_p^2 = 0.059$) all remained in the final parsimonious model for CL. The fixed factor (Participant) significantly contributed to the model ($p<0.001$; $\eta_p^2 = 0.874$). The r^2 value was 0.917 and the Adj. r^2 was 0.896.

Final Model – Kinematic variables and measures of coordination

DV - Underwater undulatory swimming velocity

The covariates identified from the resultant parsimonious models from the previous backward elimination ANCOVAS for performance and coordination variables in the first two DVs (EE_HZ and CL) formed the initial saturated model examining max *U*. The initial model contained all ten of the identified covariates (Shoulder-hip wave, knee-ankle wave, MARP foot v thigh, MARP Heave v Pitch angle; shoulder amplitude, knee amplitude, hip amplitude, max hip velocity, max knee angle velocity and mean absolute AoA).

The final parsimonious model for max *U* revealed knee-ankle wave velocity ($p<0.001$; $\eta_p^2 = 0.285$) and max knee angle velocity ($p<0.001$; $\eta_p^2 = 0.115$) to account for a large amount of the variance in max *U* with $r^2 = 0.954$ and Adj. $r^2 = 0.944$. The

fixed factor (Participant) significantly contributed to the model ($p<0.001$; $\eta_p^2 = 0.900$). When the fixed factor (Participant) was removed from the model and the ANCOVA re-run, the explained variance reduced with $r^2 = 0.544$ and the Adj. $r^2 = 0.535$, indicating a strong reliability on the participants own UUS technique in the production of max *U*.

The BE ANCOVA models conducted to analyse the kinematic variables in relation to EE_Hz and CL contained six and five covariates in their respective parsimonious models. The explained variance (Adj. r^2) for each of the respective final parsimonious models was large (EE_Hz Adj. $r^2 = 0.874$; CL Adj. $r^2 = 0.880$). Shoulder amplitude, knee amplitude, max hip angle velocity and max knee angle velocity in the EE_Hz parsimonious model achieved a large effect-size statistic (as denoted by $\eta_p^2 > 0.1379$; Cohen, 1988; Richardson, 2011), with Knee ROM and Mean Abs AoA achieving a medium effect size ($\eta_p^2 > 0.0588$). However, for the CL parsimonious model, only knee amplitude achieved a large η_p^2, with shoulder amplitude, max hip angle velocity and mean Abs AoA having a medium η_p^2 and hip amplitude classified as having a small η_p^2 ($\eta_p^2 < 0.0588$).

For the BE ANCOVA models completed to analyse the relationships between the measures of coordination and both EE_Hz and CL; the same four covariates (shoulder-hip wave, knee-ankle wave, MARP foot-thigh and MARP Heave v Pitch angle) were found to make a statistically significant contribution ($p<0.05$) to the final parsimonious models for both EE_Hz and CL. In addition, both parsimonious models

were found to explain a large proportion of variance in their respective DVs (EE_Hz Adj $r^2 = 0.932$; CL Adj $r^2 = 0.896$).

However, while both models demonstrate comparable ability for explaining the variance in their respective DVs, there are differences in the respective covariates effect size values between the BE ANCOVA models. In the EE_Hz parsimonious model shoulder hip wave, knee-ankle wave and MARP Foot v Thigh all produced large values of η_p^2 and MARP Heave v Pitch angle achieving a medium effect size. For the CL parsimonious model only knee-ankle wave and MARP Foot v Thigh achieved a large effect size, while shoulder-hip wave and MARP Heave v Pitch angle resulted in a medium effect size.

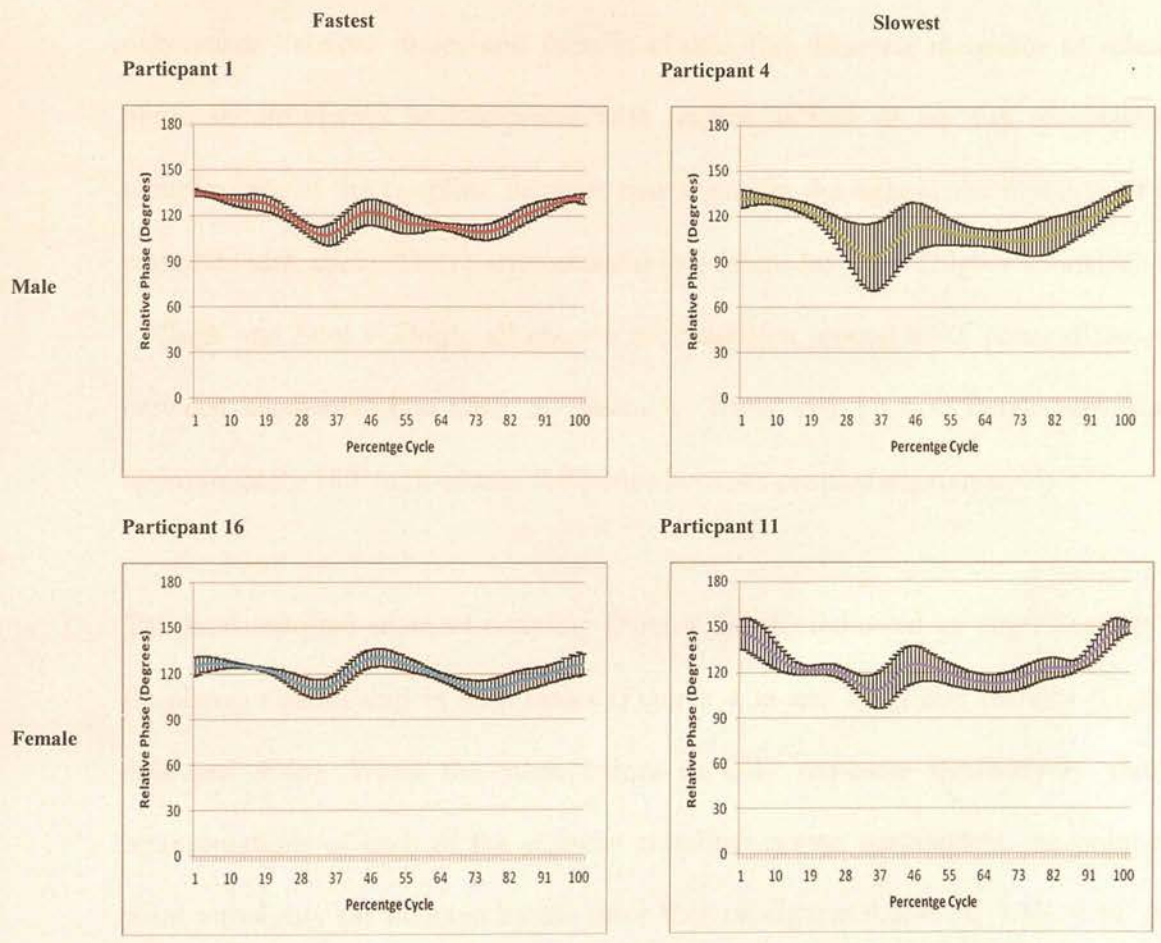
Continuous Variables - Continuous Relative Phase data

The CRP data for the swimmers showed qualitative differences in phase relationships over the kick cycle and difference in variability between the fastest and slowest swimmers (both male and female) for a number of CRP ensemble curves.

Increases in Heave v Pitch angle CRP variability can be seen (Figure 4.2) between 20% and 65% of the kick cycle in the slowest male swimmer when compared to the fastest male swimmer. This period of the cycle corresponds to the end of the upstroke of the kick and the transition to the down stroke. The Heave v Pitch angle CRP variability reported for the slowest female swimmer in comparison to the fastest shows a marginal increase in variability across the entire kick cycle. The CRP relationships for Heave v Pitch angle in the skilled age-group swimmers included in

the present study do not conform to 75° optimal relationship found in aquatic animals (Anderson *et al.,* 1998), with females achieving a MARP Heave v Pitch relationship of 117.4° ± 4.53° compared to males 118.9° ± 4.41°

Figure 4.2 Heave and Pitch CRP for Fastest and Slowest Underwater Undulatory Swimmers



Exemplar graphs of the mean values of six cycles. Error bars represent ± S.D (individuals) at each point in the normalised cycle. Max *U*: Participant 1=1.4m.s.$^{-1}$; Participant 4=1.12m.s.$^{-1}$; Participant 16=1.46m.s.$^{-1}$; Participant 11=1.05m.s.$^{-1}$

Continuous relative phase relationship patterns are (qualitatively) similar across all swimmers, in that even between the extremes of performance (slowest v fastest) the mean CRP values for each ensemble curve patterns concentrate around a clear phase difference for each set of segment couplings. However, MARP for Foot v Shank, Shank v Trunk and Shank v Thigh, all show statistically significant ($p<0.05$) differences between males and females (Table 4.2). Discrete measures of relative phase should always be interpreted with caution as they do not full elucidate the complexities of the coupling between two segments throughout the duration of the complete kick cycle. The relative phase relationships between Thigh v Trunk, Shank v Thigh and Foot v Thigh, all show a concentration around a 90° phase difference between segments. The CRP for Shank v Trunk and Foot v Trunk both show approximately 180° (anti-phase) difference between coupled segments.

The final reported segment coupling (Foot v Shank) indicated an approximately 0° (in-phase) relationship in both males (Figures 4.3a and 4.3b) and females (Figures 4.4a and 4.4b). While the mean values of CRP represent qualitatively similar representations of each of the segment couplings across participants, the point-by-point variability (as denoted by the error bars on figures 4.2, 4.3a, 4.3b, 4.4a and 4.4b) does highlight a difference between the fastest and slowest swimmers, in both male and female participants. In figures 4.3a and 4.3b (males) the CRP for Thigh v Trunk shows increases in CRP variability around the start–end points of the kick cycle in the slowest male swimmer compared to the fastest. The Foot v Thigh and Shank v Thigh CRP relationships, both show increased variability throughout the kick cycle.

Figure 4.3a Continuous relative phase: Fastest male swimmer

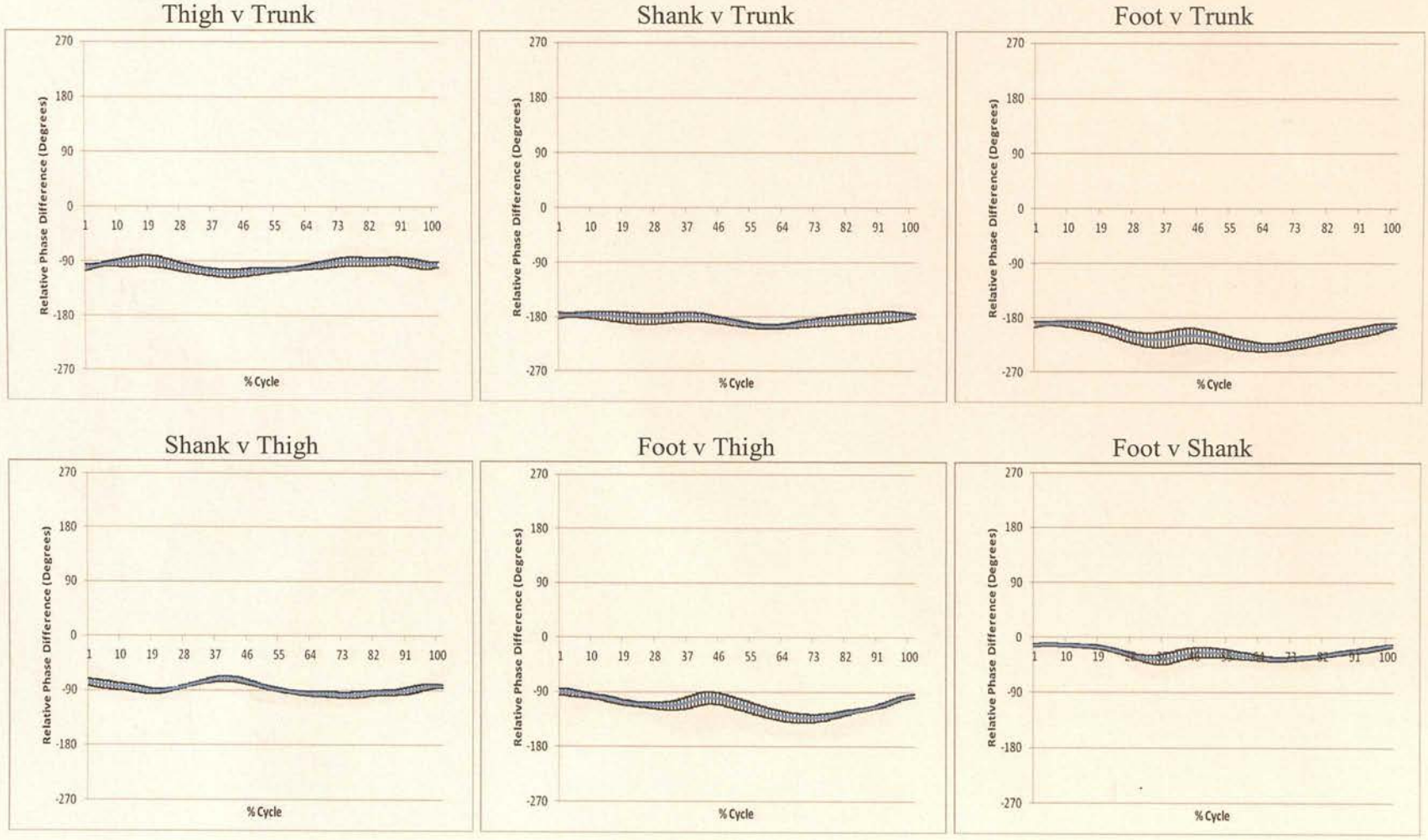


Figure 4.3b Continuous relative phase: Slowest male swimmer

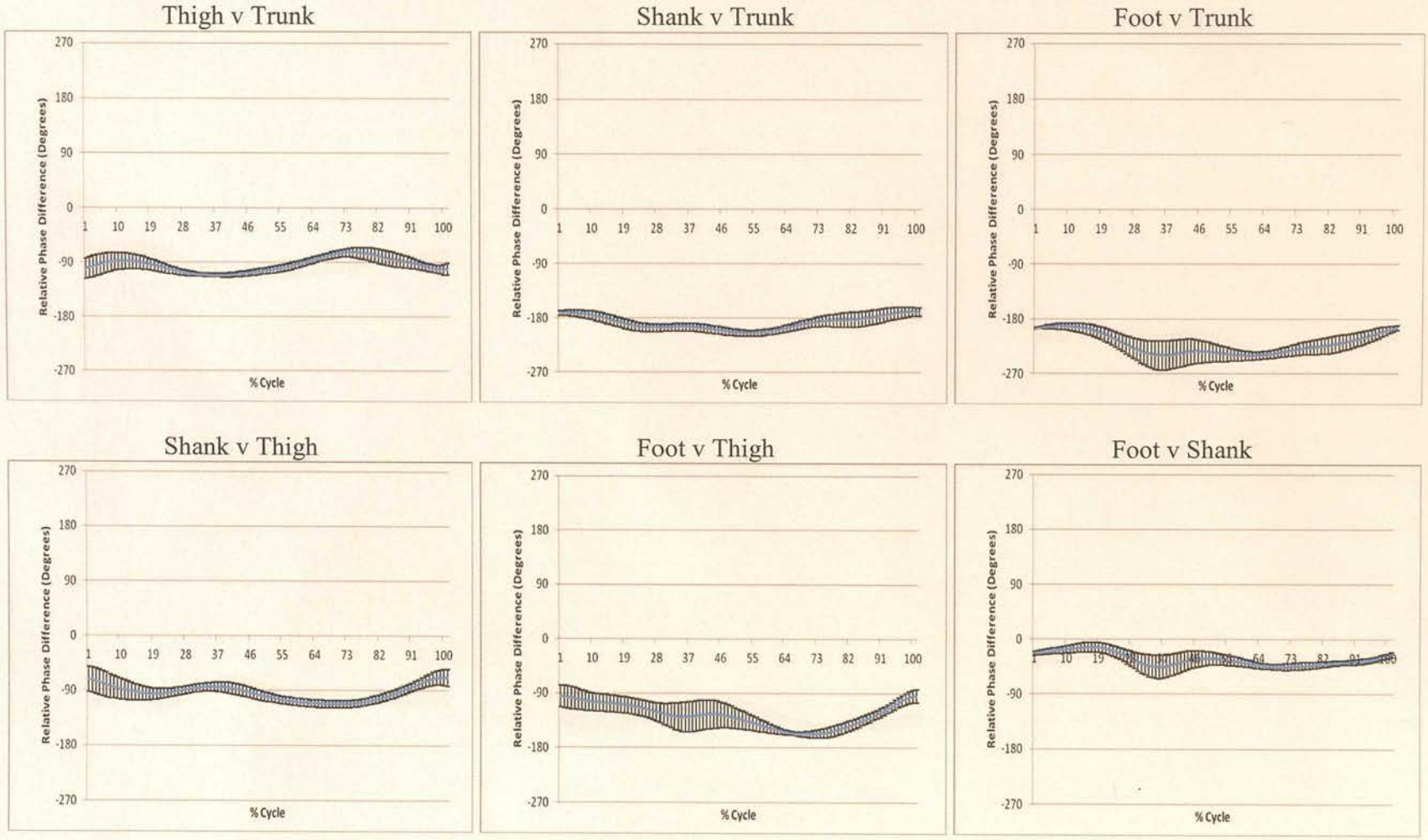


Figure 4.4a Continuous relative phase: Fastest female swimmer

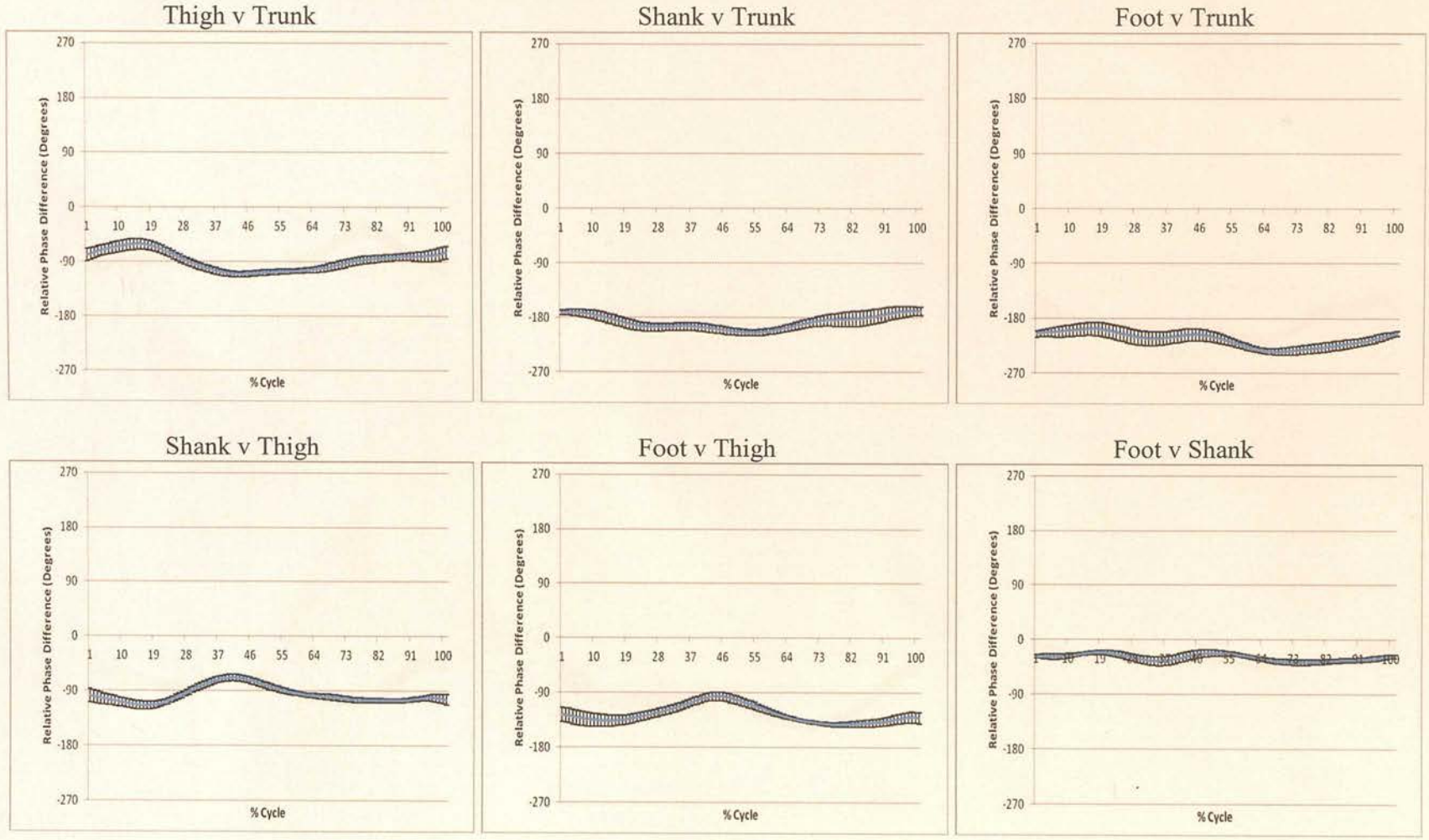
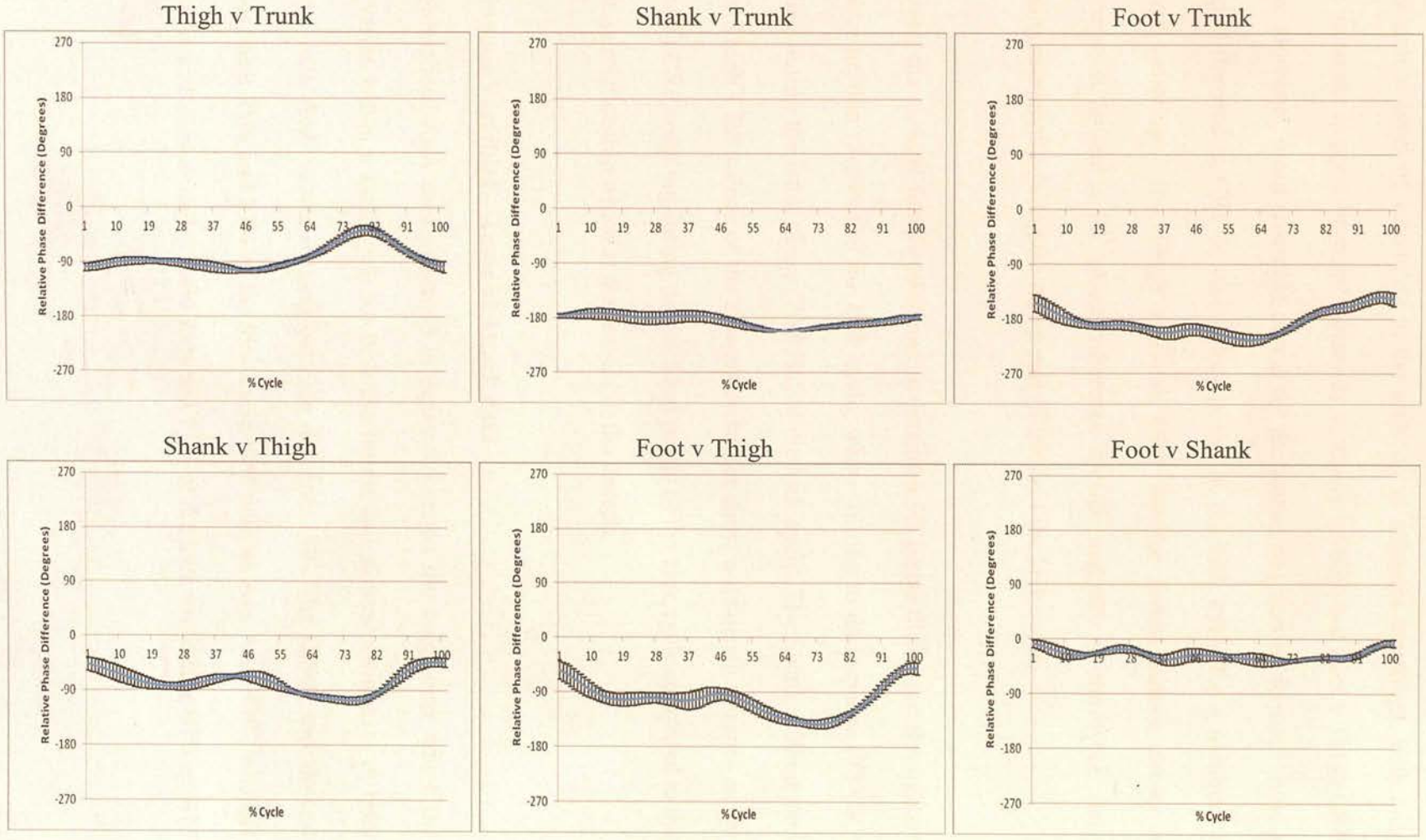


Figure 4.4b Continuous relative phase: Slowest female swimmer



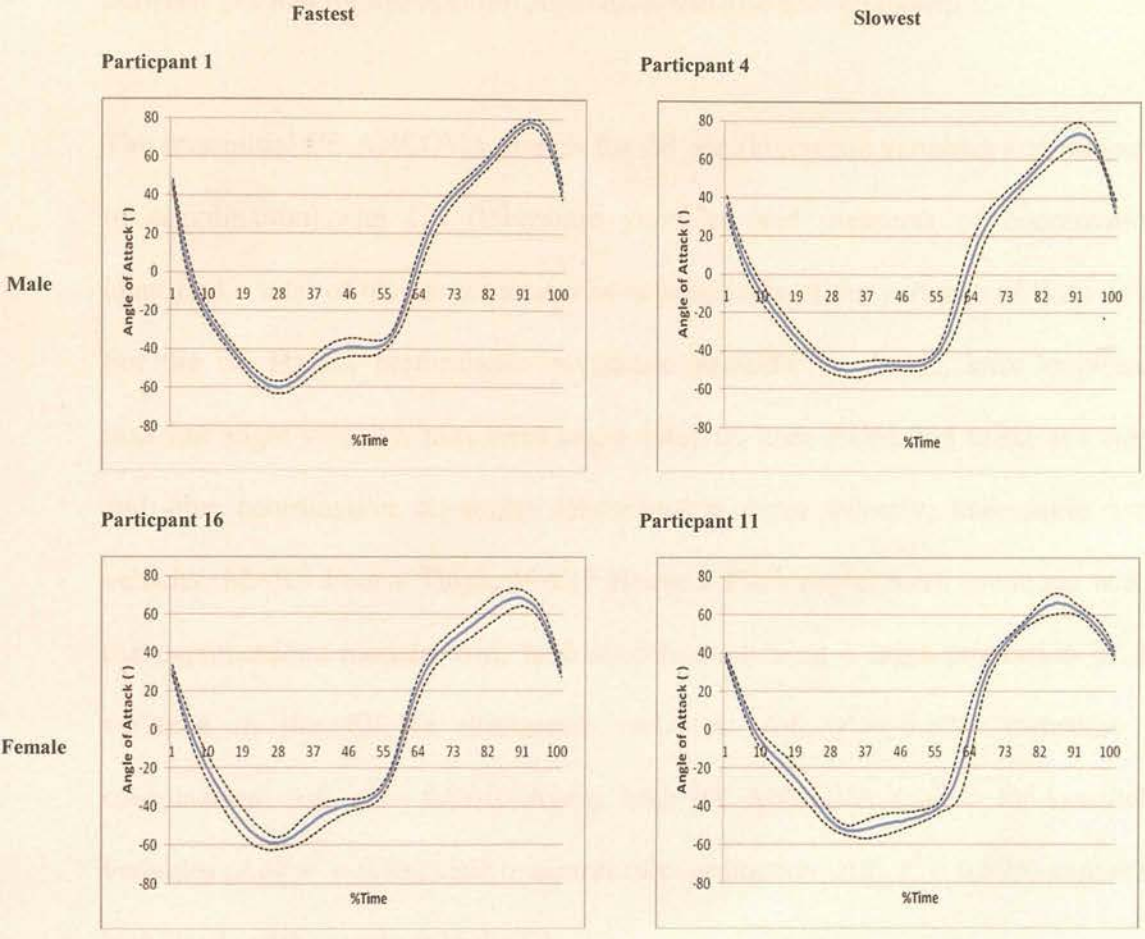
The figures (4.4a and 4.4b) representing the fastest and slowest female swimmers shows similar level of variability in the majority of segment couplings, with only slight increases in point-by-point variability in Shank v Thigh and Foot v Thigh CRP values. However, mean ensemble curves for the fastest and slowest females show a greater difference in CRP at certain key points in the kick cycle for a number of segment couplings. The Thigh v Trunk CRP for the fastest female shows a concentration around a 90° phase difference for the majority of the cycle; only deviating marginally during the initial part (5-20%) of the kick cycle.

However, the slowest female swimmer maintains a 90° phase difference throughout the same portion (5-20%) of the kick cycle, while shifting to an in-phase (0°) CRP coupling during the latter phase (70-85%) of the kick cycle. The Shank v Thigh and Foot v Thigh CRP values of the slowest swimmer show a tendency towards an in-phase (0°) CRP coupling during the start-end points of the kick cycle compared to the 90° phase relationship which is maintained in the fastest.

Continuous Variables – Angle of Attack data

The normalised AoA data presented in figure 4.5 shows the range over which the AoA varies within a kick cycle for both the fastest and slowest swimmers of both genders, with AoA values ranging between -60° and +80°. The fastest and slowest females spent 28% and 27% of the kick cycle time with an Abs AoA <30°, whereas the fastest and slowest males spent 22% and 21% of the kick cycle time with an Abs AoA <30°.

Figure 4.5 **Angle of attack for fastest and slowest underwater undulatory swimmers**



Solid line represents the mean point by point AoA from six cycles representing UUS; Dotted lines represent point by point sample SD for each individuals six cycles.

4.4 Discussion

The purpose of the study was to identify key kinematic measures of performance and coordination for maximal undulatory underwater swimming in skilled age-group swimmers. To this end two specific aims were addressed, (1) identify which of the kinematic variables and measures of coordination were best able to predict max *U* in skilled age-group swimmers, and (2) provide empirical evidence to help justify the selection of an order parameter, to enable future studies to examine UUS system dynamics. Also, while not identified *a priori* as a specific aim of the present study; in

achieving the stated aims, an exploration of the differences in the kinematics of UUS between genders for this specific population was also accomplished.

The four initial BE ANCOVA models for EE_Hz (kinematic variables and measures of coordination) and CL (kinematic variables and measures of coordination) identified a total of eleven covariates as determinants of the variance of these DVs. For the EE_Hz six performance covariates (shoulder amplitude, knee amplitude, max hip angle velocity, max knee angle velocity, knee ROM and mean abs AoA) and four coordination covariates (shoulder-hip wave velocity, knee-ankle wave velocity, MARP Foot v Thigh, MARP Heave v Pitch angle) were contained within the parsimonious models, with both models explaining a large proportion of the variance in the EE_Hz (kinematic variables: Adj. r^2= 0.874; measures of coordination: Adj. r^2 = 0.880). Again, both BE ANCOVA models for kinematic variables (Adj. r^2 = 0.932) and measures of coordination (Adj. r^2 = 0.896) explained high levels of the variance in the CL.

The difference in the *r*-values for some of the kinematic variables and measures of coordination identified as covariates within both the parsimonious models for EE_Hz and CL underlies the aforementioned disparity evident within this sample of age-group swimmers and serves to further demonstrate the competing factors which determine the max *U* and the manner by which it can be achieved; namely the requirement to simultaneously produce a propulsive impulse and minimise AD with the same movements (Ungerechts, 1984).

Understanding that greater UUS velocities are achieved by increasing the magnitude of the propulsive impulse relative to the AD experienced, it then becomes clear that the same max *U* can be attained in a number of different ways. For example the same max *U* can be achieved via large undulatory movements which seek to maximise propulsive impulse production with a correspondingly high AD (high energy requirement/cost), or via smaller movements which produce a reduced amount of propulsive impulse but simultaneously minimise AD experienced. The skilled underwater undulatory swimmer would attempt to maximise propulsive impulse by employing optimal amplitudes of the end-effector in conjunction with the coordinated amplitudes of the preceding sections of the body in a temporally structured manner such that minimises flow separation (Tokomaru and Dimotakis, 1991; Triantafyllou, 2002) and maximises energy reuse from the vortices shed as 'body wake' further up the undulating body (Triantafyllou, 1991; Anderson *et al.*, 1998).

An example of this competing element of propulsive impulse production and AD minimisation in the coordination observed within the current population is the strong positive relationships between shoulder amplitude and CL (r = 0.620) showing that those with higher CL display a concomitant increase in shoulder amplitude. However, the strong negative relationship between shoulder amplitude and EE_Hz (r = -0.620) demonstrates a strong statistical relationship between age-group swimmers with a higher EE_Hz displaying lower shoulder amplitudes. This shows the requirement to minimise AD via limiting the cross sectional area relative to the flow (low shoulder amplitude) and minimising flow separation along the body via the

coordination of the segment undulations (which may require greater shoulder amplitudes (e.g. Taneda, 1978; Barret *et al.,* 1999), while simultaneously acting as an inertial damper (Connaboy *et al.,* 2007a) to enable higher levels of EE_Hz to produce a greater propulsive impulse. Another possible explanation for the disparity evident is that there are a variety of solutions (patterns of kinematics) being employed to achieve the movement problem within the current skilled age-group sample.

The final parsimonious model for max *U* revealed knee-ankle wave velocity ($p<0.001$; $\eta_p^2 = 0.285$) and max knee angle velocity ($p<0.001$; $\eta_p^2 = 0.115$) to account for a large amount of the variance in max *U* with $r^2 = 0.954$ and Adj. $r^2 = 0.944$. The fixed factor (Participant) significantly contributed to the model ($p<0.001$; $\eta_p^2 = 0.900$). The two key covariates for max *U* both showed strong individual correlations with max *U*. While max knee ankle velocity showed a strong positive *r* value ($r = 0.757$ females; 0.556 males and 0.639 pooled; $p<0.001$), knee-ankle wave velocity showed a strong negative relationship ($r = -0.745$ females; -0.670 males and -0.661 pooled; $p<0.001$). This may appear counterintuitive. However, it should be remembered that the negative relationships occur as a consequence of relative directions of each of the velocities. As max *U* increases the wave velocity decreases, the negative value of wave velocity depicts the direction relative to the forwards travel of the swimmer. Therefore, the relationship shows that as max *U* increases the propulsive wave velocity is in effect increasing.

A fixed factor (Participant) was included in all the BE ANCOVA models. However, when this fixed factor was removed from the final 'parsimonious' model for max *U*, and the ANCOVA recalculated, the predictive quality of the model reduced substantially (r^2 =0.544, *Adj.* r^2= 0.535). This reduction in Adj. r^2, indicated a reduction in the explained variance from 95.4% down to 53.5%, demonstrating that the individual manner in which the age-group swimmers are achieving max *U* is largely dependent on the participant's own UUS technique employed and that the individual UUS technique is an important predictor of greater max *U*.

The identification of max knee angle velocity and knee-ankle wave velocity in the final BE ANCOVA model, suggest that the movements at this section of the body (knee to ankle) are crucial to the overall performance of UUS. As the propulsive waveform is produced and maintained along the length of the body, the identification of these two variables suggests that the successful transmission of the propulsive waveform is dependent largely on the successful negotiation along this knee to ankle section of the swimming body. Thus, it is suggested from the data from the present study that the production of a high angular velocity at the knee together with increased propulsive wave velocity between the knee and ankle acts to enable the production and maintenance of an effective propulsive waveform resulting in greater max *U*. This is in agreement with the findings from Ungerechts *et al.* (2000) study of vortex traces in UUS, which suggested that the vortex generation into the wake is enhanced by a whip-like action through the legs and feet, requiring high knee angular velocity.

The identification of these two covariates indicates that successful UUS also requires the temporal structuring between these relative motions to be coordinated to ensure that maximal levels of knee angular velocity can be achieved and effectively transmitted to produce high propulsive wave velocity between the knee and ankle. The importance of the movements at, or around the knee becomes even more apparent when the BE ANCOVA model for the kinematic covariates and CL are considered.

The final parsimonious model for CL included knee amplitude; highlighting the importance of the vertical movements of the knee, this time with specific reference to achieving greater horizontal displacement of the body per kick cycle. Cohen *et al.* (2012) demonstrated that the maximum cross-sectional area of the body relative to the oncoming flow occurs at the point of maximum knee flexion during maximal UUS. Therefore, the influence of knee amplitude on CL, in conjunction with the identification of max knee angle velocity and knee-ankle wave velocity in the final BE ANCOVA model, emphasises the importance of the magnitude and timing of the movements at the knee and their effects on max *U*. This highlights the requirement for coordinated temporal oscillations of neighbouring segments to minimise flow separation along the body (Taneda, 1978; Barret *et al.,* 1999) as a consequence of greater knee amplitudes.

However, Ungerechts (1984) warned of the direct application of vorticity control mechanisms seen in highly adapted and efficient aquatic animals, stating that their application is limited due to the restricted morphology of the human body in the

dorso-ventral direction. Although the mechanisms by which highly adapted aquatic animals overcome the hydrodynamic constraints to achieve effective and efficient UUS locomotion may not all be achievable in human UUS, it is these same hydrodynamic constraints which limit human attempts at UUS. Therefore, the UUS movements that occur and their interaction with the hydrodynamic environment can be analysed using the same means.

Given the restricted morphology of a human underwater undulatory swimmer in comparison to that of specifically adapted aquatic animals, with ability to flex and bend along the entire length of their body equally in both directions; it would appear that the movements at the knee (and their temporal structure) are extremely important to ensuring an effective UUS performance. As the knee is only able to flex and extend through a limited range of movement due to its anatomical structure, the capacity to generate and/or maintain the propulsive waveform is somewhat compromised, compared to aquatic animals. Likewise, the anatomical limitations of the knee joint impact on the effectiveness with which the undulatory motions can act to minimise flow separation and/or recapture and reuse energy previously shed into the body wake. In addition, the range of movement achieved at the knee (and its temporal structure) in relation to the undulatory movement of the body as a whole, determines the extent of the amplitude at the ankle/end-effector. Therefore, given the findings of the final BE ANCOVA model for max U and the previous empirical evidence (Ungerechts, 2000; Hochstein and Blickhan, 2011; Hochstein *et al.*, 2012; Cohen *et al.*, 2012), the selection of a measure or measures of coordination to act as

an order parameter for future studies should incorporate the actions of the knee to capture the state of the dynamic system.

The AoA data from the present study was consistently outside the 15°-25° range suggested for optimal thrust production (Sfakiotakis *et al.*, 1999; Videler and Kamermans, 1985; Triantafyllou *et al.*, 1993). The data presented in figure 4.5 for both the fastest and slowest swimmers of both gender indicates in excess of 90% of total UUS cycle time was spent outside this 15°-25° range. It has been previously suggested that AoA values in excess of 30° will result in a reduction of both thrust and efficiency, as this 30° AoA may represent the upper limit for oscillatory systems (Chopra, 1976). The high values found within this age-group UUS sample would suggest that the generation of an effective propulsive lift force, via the maintenance of an AoA within the prescribed range is not the primary goal of the swimmers and/or the anatomical limitations of the knee and ankle act to limit the opportunity to maintain the AoA within the optimal range throughout an entire kick cycle.

Recent data presented by Hochstein and Blickhan (2011) provide support for the notion that both statements are true, as they showed evidence to suggest that vortex-recapturing as a mechanism to enhance UUS is being utilised by elite swimmers. Therefore, while there may be a lift force generated throughout specific portions of the kick cycle when the AoA of the end-effector is within the optimal range, the primary purpose of the relative changes in orientation of the end-effector with respect to the flow may be to act to minimise AD via the effective recapturing of previously shed (body wake) vortices and the successful transmission of these into an

optimal wake structure (i.e. reverse-Karmen vortex street). Further research is required to determine the efficacy of Hochstein and Blickhan (2011) findings within age-group swimmers and examine the premise that the higher AoA values employed are acting to recapture previously shed vortices.

Similarly, the CRP relationships for Heave v Pitch angle in the skilled age-group swimmers included in the present study do not conform to the idealised values for simultaneous optimisation of thrust production and AD minimisation as they exceed the 75° optimal phase relationship found in aquatic animals (Anderson *et al.,* 1998). The females' mean MARP for Heave v Pitch angle was 117.4° ± 4.53°, with males achieving a mean MARP of 118.91° ± 4.41°, suggesting that the age-group swimmers are seeking to maximise the propulsive impulse outside an effective range. However, what cannot be extracted from the MARP Heave v Pitch angle (discrete) data are the temporal aspects of the Heave v Pitch angle relationship with the effective control of vorticity. As the dynamic eddying motions are passed along the length of the swimming body, the temporal control and relative orientation of the end-effector becomes crucial to the manipulation and transmission of this energy into an effective wake structure (Triantafyllou et al., 1993; Anderson et al., 1998; Triantafyllou et al., 2002).

Hochstein and Blickhan, (2011) have shown that during UUS skilled swimmers show large vortex separation at the head, knees and feet, effectively meaning a loss of energy from the system. If the skilled swimmers are to optimise UUS performance, then perhaps the CRP relationships for Heave v Pitch angles observed

represent an effective mechanism by which this lost energy can be saved by vortex recapturing, i.e. reusing energy previously lost in the body wake earlier (upstream) by effective coordination and manipulation of the caudal aspects of the body and the end effector (Hochstein and Blickhan, 2011). However, more research is required over a greater range of swimmer abilities to determine if this relationship varies/is maintained with max *U*, and establish the controlling mechanisms which determine if, and how the vortices are recaptured before being shed into the resultant wake.

Increased Heave and Pitch CRP variability is evident between 20% and 65% of the kick cycle in both the male and female slowest swimmers relative to the variability observed in the fastest. This period of the cycle corresponds to the end of the upstroke of the kick and the transition to the down stroke; a portion of the UUS cycle critical in controlling the vorticity due to the marked change in direction of the end-effector and the increased risk of flow separation (Hochstein *et al.,* 2012). Increased variability may signify reduced control over the minimisation of this vortex shedding and an associated increase in AD. Acknowledging the importance of Heave v Pitch angle (its variability and stability) in the successful execution of max *U*, it would be prudent for future studies to incorporate this variable as a means to determine the state of the UUS system.

Females had significantly greater amplitude at the wrist than males (Table 4.1), suggesting that they were less able to utilise the arm segment as an inertial damper (Connaboy *et al.,* 2007a). However, a more likely explanation is this may be occurring as a consequence of the significantly greater 5th MPJ amplitude achieved

by the females, with the increased wrist amplitude resulting in direct response. The slightly higher female wrist amplitude may also increase the cross-sectional area relative to the oncoming flow and therefore result in concomitant increase in active drag (Vorontsov, and Rumyantsev, 2000). However, examining the wrist amplitude in isolation and making predications on its effects on overall performance should be undertaken cautiously.

As there are no significant difference in max *U*, EE_Hz or CL between males and females, then the females may be acting to solve the movement problem (maximising thrust while simultaneously minimising drag) via different mechanisms, i.e. better coordination of the undulatory movement to minimise AD at a given relative velocity. These adaptive requirements may well represent the statistical differences in certain kinematic measures of coordination as female adopt different coordination strategies to achieve similar performance output levels (Tables 4.1 and 4.2).

The variables identified as being significantly different (Tables 4.1 and 4.2) by gender, highlight that while both males and females are aiming to achieve the same goal (max *U*), their respective (interacting) idiosyncratic constraints require them to achieve this goal by different means, i.e. slight variations in movement patterns/coordination strategies (Holt, 1998). Given that there are no statistically significant differences between the key kinematic variables (max *U*, EE_Hz and CL) by gender, the statistical differences apparent between genders in the identified factors suggest that certain constraints (anthropometry, strength, flexibility, etc.) may be acting to influence the kinematics observed. Seifert *et al.* (2004), came to similar

conclusions when examining disparities in the arm coordination between skilled male and female front crawl swimmer, explaining that anthropometric differences between genders resulted in adapted patterns of coordination to achieve the same aim (maximisation of front crawl swimming velocity). Within the present study, the higher ROM observed in the females (Table 4.1) provides some support that the females are able to exploit their constraints to achieve similar levels of max *U*. However, as no direct measurements of males and/or females maximal flexibility (ROM) for any of the joint were taken, this cannot be confirmed.

Another interpretation of the data would suggest that while some of the differences observed between genders are statistically significant, the magnitude of the differences observed do not represent practically relevant variations which impact on performance, suggesting that these specific variables are not important, or certainly not as important to the overall production of maximal levels of max *U*. However, further study is required to confirm the efficacy of either of these assertions.

The results presented in Tables 4.3 and 4.4 highlight a number of kinematic variables and measures of coordination that demonstrate further disparities evident between genders. Most notable are the differences in Pearson product–moment correlations (*r*-value) between CL and max *U* (males: 0.815, females: 0.103), Mean Abs AoA and CL (males: -0.554, females: -0.134), Max AoA and max *U* (males: -0.186, females: 0.807), and MARP Heave v Pitch angle and CL (males: -0.182, females: 0.704). However, interpretation of these values in isolation should be undertaken with caution in terms of any attempt to confirm causal relationship, assess predictive

accuracy and/or their relative contribution to an understanding of max *U* performance in age-group swimmers. The utilisation of the BE ANCOVA model provides a more comprehensive account of the interrelationships between, and predictive quality of the covariates for determining the variance in max *U* (Stevens, 1992).

The data in tables 4.1 and 4.3 highlights that while statistically significant differences between the absolute values of a number of kinematic variables and measures of coordination may not be present between genders, the relationships, as denoted by the *r*-value may be markedly different, providing further support for an understanding that the constraints which are acting independently by gender are influencing the means by which the max *U* is achieved. When incorporating the results from the BE ANCOVA model, we begin to understand the importance of the individual nature of the technique(s) employed by the underwater undulatory swimmers. This suggests that there may be factors (constraints) which are common within genders which act to influence the variables identified as statistically different by gender.

The same principle can be employed to understand any disparities evident with the total sample of underwater undulatory swimmers, in that, the individuals' own constraints act to limit their observed behaviour, and given the reduction in the explained variance with the removal of the participant as a fixed factor in the BE ANCOVA model there are obviously a number of different solutions to the movement problem being employed. The availability of a number of different

solutions to a task (motor equivalence) is especially important to consider given the large number of a degrees of freedom within the present UUS task.

4.5 Conclusion

The data presented within the present study provide new insight to understand the key determinants of UUS performance in skilled age-group swimmers. The identification of the eleven covariates within the initial BE ANCOVA models for EE_Hz and CL, highlight the competing elements of propulsive impulse production and AD minimisation, and the importance of understanding that the same movement problem can be accomplished with a variety of solutions. The subsequent identification of the two covariates (maximum knee angle velocity and knee-ankle wave velocity) as key determinants of max *U* provides new information as to the relative importance of the kinematics of the knee to the transmission and maintenance of the propulsive waveform. The identified importance of the movements at or around the knee suggests that future studies that seek to examine the state of the UUS system dynamics should incorporate measures of coordination which include a contribution from the knee kinematics. Likewise the identified importance of MARP Heave v Pitch angle within both the initial BE ANCOVA for EE_Hz and CL suggests that it should also be considered when looking to observe and examine changes in the state of the UUS system dynamics as a consequence of a specific intervention (e.g. training) and/or changes in a control parameter (e.g. imposed frequency). The results from the present study do not clearly identify a single suitable order parameter. However, the established importance of the kinematics and coordination at and around the knee and the relative phase between

Heave v Pitch angle concentrate the focus for future research in establishing suitable order parameter(s).

The results of the present study also highlighted the difference between males and females when performing max *U*. Importantly, it is evident that the individual swimmers idiosyncratic constraints and their manifestation within their own technique are crucial to an understanding of UUS performance. Therefore, while is important to recognise that no single style or technique of UUS can be applied to all swimmers, coaches and scientists should continue to examine the means/mechanisms by which the individuals own constraints can be manipulated (increasing strength, flexibility, adaptations of swimming posture, etc) to enable the swimmers to overcome the hydrodynamic (environmental) constraints and further optimise UUS.

Finally, the use of continuous measures in combination with discrete measures of performance/coordination should be repeated within any future studies to enable comprehensive analysis of the UUS system dynamics and ensure that the subtle but important differences in coordination can be examined.

Chapter 5

Study 3:

Effects of imposed cycle frequency training on the coordination and performance of underwater undulatory swimming in skilled age-group swimmers

5.1 Introduction

The importance of movement frequency to an overall understanding of coordinated action and skilled movement cannot be understated, whether it is the frequency of an end-effector (global) or the component frequencies of various (local) subsystems which are coupled within a coordinative structure. The frequency (relative or otherwise) of movement has been used as a means to classify, understand, predict and/or determine the efficacy and efficiency of the movements produced (Swaine & Reilly, 1983; Kaneko *et al.,* 1987; Van Emmerik, *et al.,* 1989; Pelayo *et al.,* 1997; Neptune & Hull, 1999; Goosey *et al.,* 1999; Brisswalter *et al.,* 2000). Primarily, imposed cycle frequencies have been utilised, as a control variable/parameter with manipulations used to perturb the coordinative structure(s) of the system, to assess the short-term impacts on the stability and topological dynamics of the resultant movement behaviour in a self-organising system (Smoll, 1975; Smoll and Schulz, 1978; Van Emmerik *et al.,* 1989; Carson *et al.,* 1999; Carrol *et al.,* 2001; Semjen, 2002; Torre *et al.,* 2007; Ford *et al.,* 2007).

Yanai and Hay (2004) recognised that a limitation of previous research into the concept of optimal cycle frequency is the assumption that humans are 'self-optimising machines', which ultimately evolve towards the most economical/advantageous solution to the movement equation. This 'solution to the movement equation' refers to an optimal movement response to the underlying constraints and movement-system characteristics which regulate and/or restrict opportunities for action. According to Yanai and Hay (2004) this limitation is a failure to acknowledge that a particular cycle frequency may have become the most

efficient and/or effective in a skilled performer as a consequence of neurophysiological adaptation brought about by years of repetition at a particular cycle frequency, rather than the successful development of the optimal solution to the movement equation.

Also noted is that while a system can be viewed as self-organising this does not necessarily equate to self-optimising. Both Walter and Swinnen, (1994) and Rousanoglou and Boudolos, (2006) have suggested that in the process of learning to optimise action, performers may produce preferred patterns of coordination which represent a sub-optimal strategy. Walter and Swinnen (1994) explained that these sub-optimal coordinative strategies are consistent with the optimisation of a parameter which does not coincide with the most effective and/or efficient way to execute a skill. Rousanoglou and Boudolos (2006), found sub-optimal movement behaviours at preferred hopping cycle frequencies for a number of performers, suggesting that further exploration of the perceptual-motor workspace may be required before those performers could reap the rewards associated with achieving resonance.

Given an understanding that skilled performers may adopt coordinative strategies (locally stable attractor states) which result in sub-optimal performances, then research is required which determines the efficacy of methods employed to perturb coordination away from these sub-optimal states and establish the success with which they can promote further search of the perceptual motor workspace for more effective and efficient solutions (Wilson *et al.,* 2008). Furthermore, investigations are

required to determine whether imposing a frequency can be effective in developing coordination that enables more optimal performance. However, the possibility exists that the act of imposing a frequency can affect performance as a factor additional to the effect of the frequency itself. Therefore, the first step in such an investigation is to determine how the imposition of a frequency equivalent to the naturally selected preferred frequency affects performance.

The recognition from the previous chapter (Study 2) that the individual skilled age-group swimmers are performing UUS with a variety of idiosyncratic coordination patterns, then further examination of the methods by which the interacting organismic and task constraints can be manipulated are required to enable the swimmers to overcome the hydrodynamic (environmental) constraints and further optimise UUS. Consequently, the identification of the key determinants of UUS in skilled age-group swimmer in the previous chapter (Chapter 4) provides a focus for the continued search for the identification of an appropriate order parameter which accurately encapsulates the system behaviour for UUS and enables these behaviours to be monitored throughout a period of training and testing.

As stated in Chapter 1 (Section 1.2) a number of studies have examined the assumption that preferred cycle frequency represents an optimal cycle frequency for both performance and learning. This work is exemplified by the research of Sparrow *et al.* (1999), who showed that when performing and training to improve motor economy, a self selected preferred cycle frequency was the most effective when compared to training at imposed higher (+20%) or lower (-20%) cycle frequencies.

The majority of research relating to the efficacy of training and/or learning via an imposed frequency has not typically involved imposed frequencies which are equivalent to the performers preferred cycle frequency. One exception was the study by Van Emmerik *et al.* (1989), in which it was found that both self-selected preferred cycle frequency and imposed (at preferred) cycle frequency represented the most effective ways in which performance and learning were optimised by novices learning skiing on a simulator.

The research presented above gives clear indications that enhanced performance and learning are achieved in novices when practicing at a preferred cycle frequency. However, the examination of preferred/imposed frequency training has been limited to the skill acquisition process, rather than the further development of skilled performers. Therefore, if training at a preferred cycle frequency state brings about better results in novice performers (Sparrow *et al.,* 1999) can the imposition of a preferred cycle frequency act as a mechanism to enhance further learning, adaptation and performance in skilled performers? Are the improvements associated with training at a preferred cycle frequency a consequence of the ability to freely adopt a cycle frequency and search the perceptual-motor workspace from cycle to cycle, or is it the initial benefit contained/represented in the individual already established preferred cycle frequency? Consequently, a factor which has yet to be adequately addressed is the implication of the act of imposition, i.e. is it the higher or lower cycle frequency which limits improvements in performance, economy and/or learning, or is it the very act of imposing the frequency which limits the extent of the

search of the perceptual-motor workspace and thus constrains any further improvement.

The optimisation of the cycle frequency for UUS (as outlined in a Section 1.2) is bounded by the interaction of the task, environmental and individual constraints. Therefore, cycle frequency is governed by (1) the confines of the task, namely the intent to maximise the propulsive impulse whilst simultaneously minimising AD to maximise UUS velocity, (2) the constraints of the environment which are dictated by the hydrodynamics that determine the relative success of a particular cycle frequency and specific intra-limb coordination patterns adopted, and (3) the idiosyncratic characteristics of each individual swimmer. Understanding that less skilful performers are able to attain certain markers of performance and coordination similar to those observed in highly skilled performers, while still possessing other, relatively naive patterns of coordination (Teulier *et al.,* 2006); then the purpose of training may be considered not as a promotion of a to-be-acquired pattern of movement, rather a facilitation of further exploration away from established sub-optimal preferred stable attractor states towards more task specific, higher order coordinative states (Thelen, 1986; Delignieres *et al.,* 1998).

Understanding these constraints in conjunction with an appreciation of the process by which skilled swimmers have developed a stable intra-limb coordination pattern at a preferred cycle frequency (the preferred cycle frequency at which maximal velocity is currently attained), then it would be of great interest to determine if the imposed preferred cycle frequency acts to re-launch the search of the perceptual-motor

workspace (Nourrit *et al.,* 2000), or whether the act of imposition functions as a threshold, limiting the potential for further exploration (Delignieres *et al.,* 1996; Nourrit *et al.,* 2000).

Thus, the purpose of this study was to investigate the effects of training at an imposed (preferred) cycle frequency for improving maximal UUS performance in skilled age-group swimmers. To this end four specific aims were addressed: (1) to compare the effects of training at a preferred cycle frequency and an imposed preferred cycle frequency, on the kinematics and measures of coordination of UUS in skilled age-group swimmers, (2) to establish the efficacy of using the measured coordinative structures as an order parameter to encapsulate the USS system dynamics, (3) to determine the efficacy of imposed cycle frequency training for promoting learning and adaptation in both the local and global UUS system dynamics, (4) examine the act of frequency imposition to determine its effects on performance and coordination to enable future studies delineate the effects of changing cycle frequency from the act imposition itself

5.2 Methods

5.2.1 Participants

A mixed gender group of twenty-three national age-group competitive swimmers participated in the present study. Only the data from those participants who attended all testing and training sessions were included and analysed as part of the study. Of the initial twenty-three participants, seven participants either withdrew for reasons unrelated to the study, or failed to complete all the required training and testing

sessions. A total of sixteen (eight male and eight female) national age-group competitive swimmers (Mean ± SD: Age 16.00 ± 1.37 years, Height 171.91 ± 9.09 cm, Mass 63.66 ± 12.14 kg) from the '*Elite*' squad of a local swimming club were analysed as part of the present study. Participants included in the study were selected on the basis that they had a minimum of five years competitive swimming experience (Experience: 7.01±1.71 years), had competed in a national age-group final and were a member of the clubs elite training squad. The participant selection criteria were established to ensure a level of UUS which would be representative of a 'skilled' swimmer. Prior to undertaking the study, ethical approval was granted from the University of Edinburgh ethics committee. Informed consent to participate in the study (Appendix 5 and 6) was obtained from each of the participants, in accordance with the regulations and procedures set out by the University of Edinburgh ethics committee.

5.2.2 Study Design

A two group (experimental vs. control) randomised controlled experimental study design was employed to determine the effects of the imposition of a cycle frequency equivalent to a swimmer's preferred cycle frequency on the kinematics and coordination of skilled age-group swimmers performing UUS over a 4-week training programme and a further 2-week retention period (Figure 5.0). Prior to determining the participants' baseline preferred cycle frequencies, all participants undertook a familiarisation session which consisted of eight practice trials of the experimental protocol. This familiarisation session was conducted to minimise the potential for systematic bias between data collection periods occurring as a consequence of

adaptation to the experimental protocol and to ensure the reliability of the data collected, in accordance with the findings from Study 1 (Chapter 3). The participants' mean preferred UUS cycle frequency were established in an initial 'Preferred frequency Assessment' testing session (Figure 5.0) which was conducted one week after the familiarisation session and two weeks prior to the start of the testing/training period. This two week period was required to ensure adequate amount of time to enable the participants' individual UUS data to be digitised and their preferred UUS cycle frequency accurately determined prior to the initial testing session (Session 0).

Prior to Session 0 data collection, participants were randomly assigned to either the self selected preferred cycle frequency training group (PGp - control group) or the imposed (preferred) cycle frequency training group (IGp - experimental group). During each testing session (Session 0-4 and Retention Test (RT)) all participants completed three trials of maximal UUS at their self-selected preferred cycle frequency and a further three trials at an imposed cycle frequency which was set at the participants' own preferred cycle frequency (identified during the preferred frequency assessment testing session). After Session 0 testing, weekly training commenced. Each of the weekly training periods consisted of three training blocks (each block totalling approx. 2000 m of undulatory swimming) of either imposed cycle frequency training (IGp) or preferred cycle frequency training (PGp). This training was conducted within the swimmers' scheduled training programme.

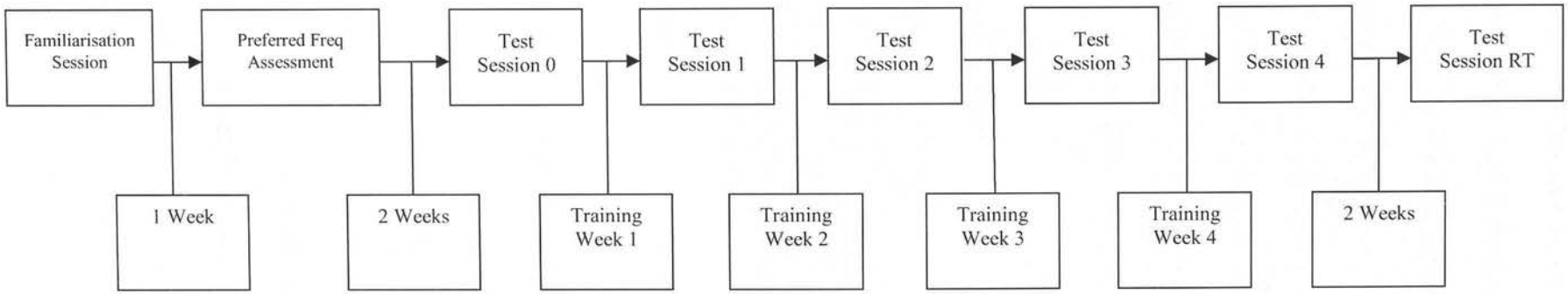


Figure 5.0 Experimental Testing and Training Schedule

The IGp and PGp training was completed on non-consecutive days (Friday - Monday - Wednesday) to allow rest between training sessions. The training week ran from one Friday to the next Friday. Testing sessions took place on a weekly basis, on the Friday prior to the first weekly training session. All the testing sessions were conducted at the same time of day on each of the testing occasions to minimise the influence of diurnal biological variation on performance (Reilly, Robinson and Minors, 1984). During the total testing and training period (nine weeks), all swimmers refrained from any UUS or specific kicking training/practice outside of that scheduled for the present study.

5.2.3 Experimental Protocol

Participants performed all swimming activities in the research pool of the Centre for Aquatics Research and Education (CARE) at the University of Edinburgh. All UUS trials were conducted using the same experimental setup, as shown in Figure 4.1. Prior to undertaking the six trials of maximal UUS (three preferred and three imposed), all participants completed a standardised twenty minute warm-up.

The experimental protocol for the self selected preferred cycle frequency UUS data collection for each of the testing sessions (0-4 and RT) was identical to that from sections 4.1.2 and 4.1.3 (Chapter 4). The experimental protocols for the imposed cycle frequency trials were identical to the preferred, with the exception of the inclusion of an external, imposed cycle frequency. A Sportpacer ™ (Logistic Design, UK) unit was used to govern the frequency of the participants UUS kicking action. The Sportpacer ™ acts as an electronic metronome, which can be programmed to emit an audible signal at predetermined intervals. The individual participants were

issued with their own personal Sportpacer unit, set at their own preferred cycle frequency (determined from the preferred frequency assessment testing session). Participants were instructed to use the audible signal to regulate the frequency of their UUS kicking action. The Sportpacer ™ unit was worn by each swimmer under their swimming cap, next to their ear.

The three imposed preferred cycle frequency trials each consisted of the participant starting from point A (Figure 4.1) at the end of the pool, pushing off the wall and swimming underwater using the dolphin leg kick with their arms out-stretched in front of them (Figure 2.2). The participants were required to swim as fast as they could, whilst matching their cycle frequency to the audible signal generated by the Sportpacer™ unit. The imposed kick cycle frequency was not regulated to control the timing phases of both the up and down beats of the kick cycle, but rather a single audible signal was used to govern the whole kick cycle so as to match the swimmers own preferred cycle frequency.

According to Ungerechts (1982) there is no discernible time difference between the up and down beat phases within the dolphin leg kick. Therefore, it is argued that using the single signal to indicate the whole cycle would reduce interference with the kicking actions of the participants, whilst still govern the kick cycle frequency. Participants were required to regulate the cycle frequency to ensure that the end of the downbeat of the kick action coincided with the audible signal generated by the Sportpacer™ unit.

The participants were instructed to accelerate over the first 10m maximising swimming velocity prior to entering the beginning of the filming area, and to maintain that velocity throughout the entire filming area while still matching the imposed cycle frequency. Each participant completed a set of three trials of imposed and a set of three trials of preferred cycle frequency maximal UUS. A five minute rest interval between trials was enforced to enable full recovery between trials and minimise the effects of fatigue. A ten minute rest period between the sets of imposed and preferred cycle frequency maximal UUS was employed to minimise the influence of the different conditions on each other. Half of each of the experimental and control participants underwent the imposed testing first and the preferred second with the remainder undertaking the preferred trials first and the imposed second. This was done to ascertain any order effects of testing on any of the kinematic data. This order was maintained throughout all testing sessions.

5.2.4 Preferred and imposed cycle frequency training

All participants from both training groups were required to undertake three training blocks per week, with each training block lasting approximately forty minutes. Training was incorporated within the elite squads' normal training times, immediately after the initial warm-up set. The IGp and PGp training was completed on non-consecutive days (Friday - Monday - Wednesday) and the training continued for a period of four weeks. The IGp were issued with their individual Sportpacer units during each session and wore them in their swimming cap for the duration of the kick training drills. The Sportpacer unit were set at the individual participants' own preferred frequency.

Each training block consisted of a series of five undulatory swimming drills:

1. **Kick Drill 1** (10 x 75 m =750 m total)

   Turn Drill: Swimmers were instructed to swim steadily (sub-maximally) using freestyle technique until 3/4 strokes out from the wall. At this point the swimmers were told to accelerate maximally into the wall, perform a tumble turn, push off from the wall and glide as they would when swimming competitively. They were then required to swim maximally using UUS and surface at, or beyond the 15 m lane marker. The swimmers performed two maximal freestyle strokes at the surface before slowing to a steady swimming pace. The cycle was then repeated to perform two sets of UUS kicking per 75 m repetition, to complete approximately 200 m - 250 m of maximal UUS within this set of kick drill 1.

2. **Kick Drill 2** (4 x 25 m = 100 m total)

   Changing orientation kicking: Participants were directed to swim at the surface with one arm outstretched in front with the other arm placed by their side. They were required to swim one repetition of 25 m maximal undulatory surface swimming in each of the four following orientations (1) prone, (2) supine, (3) left hand-side orientated towards the floor and (4) right hand-side orientated towards the floor. When swimming in the prone position the participants were advised to breath every 5 kick cycles (or when necessary).

3. **Kick Drill 3** (4 x 25 m = 100 m total)

   Board kicking: Swimmers performed alternate repetitions of maximal undulatory swimming (repetitions 1 and 3) and variable intensity undulatory swimming (repetitions 2 and 4) at the surface. The swimmers placed the floatation (kicking) board out in front of them throughout each 25 m repetition. The variable intensity (swimming velocity) undulatory swimming repetitions involved the swimmers modulating the swimming velocity i.e. four fast kick cycles followed by four slow cycles. The IGp were required to match their own individual imposed frequency throughout both maximal and variable intensity repetitions and modulate the undulatory swimming velocity via adaptations in swimming technique. The PGp were free to vary their cycle frequency to modify the swimming velocity.

4. **Kick Drill 4** (2 x 50 m = 100 m total)

   Surface kicking: Swimmers were required to swim at the surface performing the dolphin leg kick with arms outstretched in front of them. The swimmers were instructed to breathe every 5 kick cycles (or when necessary) and maintain maximal undulatory swimming velocity throughout each of the 2 x 50 m repetitions.

5. **Kick Drill 5** (4x 25 m = 100 m total)

   Resistive kicking: The swimmers placed their swimming float out in front of them with arms straight. The board was orientated to be perpendicular to the swimming direction to maximise the drag experienced. Swimmers were required to maximise velocity for each 25 m repetition.

The undulatory swimming drills incorporated a mix of undulatory swimming at the surface and underwater and both maximal and sub maximal undulatory swimming. Approximately 650 m undulatory swimming took place within each training session, with approximately half of the swimming occurring below the surface, depending on the distance covered underwater in Drill 1. This included (in Kicking Drill 5 – resistive kicking) maximal effort undulatory swimming at velocities much less than those experienced without the increased drag cause by the kicking board. Throughout all the kicking drills employed within the training programme the PGp were free to adopt any cycle frequency. The IGp were instructed to maintain their cycle frequency at the imposed frequency irrespective of the drill undertaken and the intensity required.

5.2.4 Data Collection and Processing

The participant preparation, filming and digitising procedures employed within the present study were identical to those outlined in section 3.2.3 (Chapter 3).

5.2.5 Data Analysis

The displacement data from each of the twelve individual cycles of UUS data (six imposed / six preferred) collected for each individual participant from each testing session (0-4 and RT) were processed using the same MATLAB (Mathworks, Inc) employed in section 3.2.3 (Chapter 3). The eleven discrete kinematic variables and discrete measures of coordination identified as being key determinants of UUS performance (Hz, CL and UUS Velocity) in Chapter 4, were calculated for each of the six cycles for both the preferred UUS tests and the imposed UUS tests conducted within each of the testing session (0-4 and RT) using the methods outlined in section

4.2.5 (Chapter 4). Several additional discrete and continuous variables were determined to ensure a comprehensive analysis of the effect of imposed frequency training on the performance and inter and intra-limb coordination (variability/stability) of UUS in skilled age-group swimmers.

Measures of max *U*, CL and EE_Hz were included to monitor performance changes in UUS, and were determined using the methods outlined in section 3.2.4 (Chapter 3). In addition, an analysis of the amplitude of the 5th MPJ was also included, given the empirically identified importance of end-effector amplitude in understanding the production of an effective UUS (Taneda, 1978; Barret *et al.,* 1999). Again, methods of calculation for 5th MPJ amplitude are outlined in section 3.2.4 (Chapter 3). Additional discrete measures of UUS kinematics were determined (1) Frequency Difference - the difference between the initial (baseline) preferred cycle frequency (which was used to determine the imposed cycle frequency) and the actual cycle frequency attained at both the imposed and preferred cycle frequencies tested throughout the training period (S0-S4 and RT), and (2) the Strouhal Number (*St*).

Frequency Difference

The mean difference and variance of the attained cycle frequency, with respect to the initial baseline measure of preferred cycle frequency, was recorded as a measure of the accuracy and variability of the attained cycle frequency, to determine the participants' ability to attain the imposed cycle frequency and the stability of the initial preferred cycle frequency across the training and testing period. This enabled the cycle frequency accuracy to be monitored throughout, and compared with the other variables.

Strouhal Number

The Strouhal number was included to quantify the propulsive efficiency of the UUS (Triantafyllou *et al.*, 1991; Streitlien and Triantafyllou, 1998), to help determine the efficacy of imposed frequency training as a means to improve UUS performance.

5.2.6 Calculation of additional variables

Accuracy of cycle frequency

The mean difference between the attained cycle frequency (for each tested frequency at each session) and the initial (baseline) cycle frequency was used as a measure of the accuracy with which the participants achieved both their preferred and imposed cycle frequencies.

The accuracy of each participant was calculated by,

$$\text{Mean Freq Difference} = \frac{(\Sigma f_{imposed} - f_{actual})}{n} \tag{20}$$

Where, $f_{imposed}$ is the mean baseline cycle frequency, f_{actual} is the actual frequency attained (the sum is taken for the differences between $f_{imposed}$ and f_{actual} over the number (n) of trials).

Variance of difference in cycle frequency was calculated as the standard deviation (S.D.) of differences between the actual cycle frequency attained and the baseline cycle frequency (for both imposed and preferred cycle frequencies), for each of the participants.

$$S.D. = \sqrt{\frac{\Sigma d^2 (f_{mean} - f_{actual})}{n-1}} \quad (21)$$

where, $d^2(f_{mean} - f_{actual})$ is the squared difference between mean difference between cycle frequency attained and frequency attained at baseline, and n is the total number of trials.

Strouhal number

The Strouhal number for each cycle of data was calculated using equation (2) from section 2.3.5.

Continuous relative phase – variability and stability

To examine between session variability in CRP, ensemble curves of the six cycles (representing either imposed or preferred cycle frequency from a testing session) were produced for each participant, as the mean from the six CRP curves. Three methods were employed to analyse any changes in the CRP data between testing sessions. Firstly, the mean absolute relative phase angle over a complete kick cycle were calculated using methods outlined in Hamill *et al.* (1999) and Heiderscheit *et al.* (1999) (see Chapter 4: Section 4.2.5: Equation 19) to examine discrete between session variations in CRP for each of the respective segment couplings. Secondly,

discrete measures of the variation of the ensemble CRP curve for each individual were then calculated as the root mean square error (RMSE) for the six ensemble curves for each condition (imposed/preferred). These processes were repeated for each of the coupled segment relationships mentioned above, and the results entered into the statistical calculations to determine any changes in CRP variability between sessions (stability) for each of these CRP segment couplings.

Thirdly, the point by point RMSE were calculated across each of the 101 points forming the mean ensemble curves of the six cycles for both the imposed and preferred UUS tests within each session. The point by point RMSE was used to analyse the variability of the CRP segment couplings to provide an indication of the variability and stability of the CRP ensemble curves across the training period (James, 2004).

The point by point RMSE was calculated using the following equation:

$$\mathbf{RMSE}_i = \sqrt{\sum_{i=1}^{n} \left(\frac{\sum_{j=1}^{n} \mathbf{R}_{ij}^{\,2}}{n} \right)} \qquad (22)$$

Where, $RMSE_i$ is the root mean square error for the i^{th} sample point, R_{ij} is the resultant deviation for the i^{th} point and the j^{th} cycle, and n is the number of cycles.

The separate mean ensemble curves (for each session) were plotted against each other with point by point RMSE for Session 0 included (as error bars). If the remaining Session CRP curves were found to deviate at a specific point in the kick cycle, a noteworthy difference was presumed to have occurred. The advantage of calculating the RMSE point by point is that it can highlight the extent of the variability across the entire cycle providing information with regards the discrete location within the cycle of any change in variability with respect to time (stability). Such information can be masked by only analysing differences in the average RMSE of a cycle.

5.2.7 Statistical Analysis

An initial series of twenty-five three-way (Order x Hz Tested x Session) analysis of variance with repeated measures (RM ANOVA) were conducted, with order of frequency tested (Order) as a fixed factor. This was carried out to determine if there were any effects for the order in which cycle frequency was tested, in each of the discrete kinematic and coordination variables in the respective testing conditions (preferred and imposed frequency).

Seventeen three-way (Group (2) x Freq Tested (2) x Session (6)) analysis of variance with repeated measures (RM ANOVA) were conducted, with Training Group (Group) as a fixed factor, to analyse each of the seventeen discrete kinematic and coordination variables in the respective testing conditions (Preferred frequency: Pref Freq and Imposed frequency: Imp Freq). This was undertaken to determine the effects of the imposition of an imposed frequency (Group) over the training period (Session) for both imposed frequency (Imp Freq) UUS performance and preferred

frequency (Pref Freq) UUS performance (Freq Tested). Four three-way (Group (2) x Frequency Tested (2) x Session (6)) RM ANOVAs, with Training Group (Group) as a fixed factor, were calculated to determine any differences in CRP variability (CRP RMSE) occurred in each of the four derived CRP curves (Foot v Shank, Foot V Thigh, Shank v Thigh and Heave v Pitch Angle).

Prior to all the RM ANOVA calculations, assumptions of data normality were assessed with the Kolmogorov-Smirnov statistic. Once data normality was confirmed the variables were entered into the RM ANOVA model. Greenhouse-Geisser corrections were employed when any data were found to violate the assumption of sphericity. Effect-size for the F-ratio was expressed as partial eta-squared (η_p^2), and statistical significance was set at $p<0.05$. The magnitude of η_p^2 was then compared to the values determined by Cohen (1988), to signify the relative effect: Large effect-size statistic ($\eta_p^2>0.1379$), Medium effect size ($\eta_p^2>0.0588$), or Small effect size ($\eta_p^2<0.0588$) (Richardson, 2011). Significant inter session differences were identified (for all the measured interactions) using repeated contrasts, with Bonferroni corrections made to counteract the associated effects of multiple comparisons.

5.3 Results

No order effects were found for any of the discrete variables measured signifying that the order in which the frequencies were tested did not systematically influence the results. The results presented in table 5.2 indicate that no variables were significantly different between the two training groups (PGp / IGp) at the two Freq Tested across the period of training and testing. However, there were other statistically significant interactions for other variables.

Table 5.2 RM ANOVA output data for kinematic variables and measures of coordination

Variable	Interaction/Main Effect	*p*	F	η_p^2
UUS Velocity	Session	0.132	-	-
	Gp x Session	0.272	-	-
	Freq Tested	0.492	-	-
	Gp x Freq Tested	0.133	-	-
	Freq Tested x Session	0.807	-	-
	Gp x Freq Tested x Session	0.238	-	-
Cycle Length	Session	0.608	-	-
	Gp x Session	0.401	-	-
	Freq Tested	0.461	-	-
	Gp x Freq Tested	0.696	-	-
	Freq Tested x Session**	0.005	5.850	0.295
	Gp x Freq Tested x Session	0.772	-	-
EE_Hz	Session	0.152	-	-
	Gp x Session	0.101	-	-
	Freq Tested	0.613	-	-
	Gp x Freq Tested	0.512	-	-
	Freq Tested x Session**	0.007	4.946	0.261
	Gp x Freq Tested x Session	0.891	-	-
Freq_Diff	Session	0.462	-	-
	Gp x Session	0.668	-	-
	Freq Tested	0.938	-	-
	Gp x Freq Tested	0.651	-	-
	Freq Tested x Session	0.381	-	-
	Gp x Freq Tested x Session	0.788	-	-
Strouhal Number	Session	0.711	-	-
	Gp x Session	0.615	-	-
	Freq Tested	0.919	-	-
	Gp x Freq Tested†	0.095	3.215	0.187
	Freq Tested x Session	0.228	-	-
	Gp x Freq Tested x Session	0.882	-	-
MARP Heave v Pitch angle	Session**	0.001	32.061	0.696
	Gp x Session	0.240	-	-
	Freq Tested	0.558	-	-
	Gp x Freq Tested	0.599	-	-
	Freq Tested x Session	0.684	-	-
	Gp x Freq Tested x Session	0.780	-	-
MARP Foot-Thigh	Session**	0.003	6.009	0.300
	Gp x Session	0.774	-	-
	Freq Tested	0.560	-	-
	Gp x Freq Tested	0.585	-	-
	Freq Tested x Session†	0.059	2.311	0.142
	Gp x Freq Tested x Session	0.496	-	-
Shoulder -Hip Wave	Session	0.411	-	-
	Gp x Session	0.264	-	-
	Freq Tested	0.848	-	-
	Gp x Freq Tested	0.126	-	-
	Freq Tested x Session	0.689	-	-
	Gp x Freq Tested x Session	0.137	-	-

Variable	Interaction/Main Effect	p	F	η_p^2
Knee-Ankle Wave	Session†	0.094	2.469	0.150
	Gp x Session†	0.096	2.466	0.490
	Freq Tested	0.771	-	-
	Gp x Freq Tested	0.487	-	-
	Freq Tested x Session*	0.010	4.201	0.231
	Gp x Freq Tested x Session	0.340	-	-
Shoulder Amplitude	Session	0.113	-	-
	Gp x Session	0.304	-	-
	Freq Tested	0.593	-	-
	Gp x Freq Tested	0.378	-	-
	Freq Tested x Session*	0.040	2.475	0.150
	Gp x Freq Tested x Session	0.927	-	-
Hip Amplitude	Session	0.139	-	-
	Gp x Session	0.373	-	-
	Freq Tested	0.243	-	-
	Gp x Freq Tested	0.516	-	-
	Freq Tested x Session**	0.005	3.669	0.208
	Gp x Freq Tested x Session	0.095	-	-
Knee Amplitude	Session	0.235	-	-
	Gp x Session	0.279	-	-
	Freq Tested	0.498	-	-
	Gp x Freq Tested	0.612	-	-
	Freq Tested x Session	0.689	-	-
	Gp x Freq Tested x Session	0.487	-	-
Knee ROM	Session	0.468	-	-
	Gp x Session	0.204	-	-
	Freq Tested	0.511	-	-
	Gp x Freq Tested	0.168	-	-
	Freq Tested x Session	0.442	-	-
	Gp x Freq Tested x Session	0.324	-	-
5th MPJ Amplitude	Session	0.682	-	-
	Gp x Session	0.480	-	-
	Freq Tested	0.587	-	-
	Gp x Freq Tested	0.282	-	-
	Freq Tested x Session**	0.003	5.527	0.283
	Gp x Freq Tested x Session	0.779	-	-
Max Hip Angle Velocity	Session**	0.003	6.683	0.323
	Gp x Session	0.634	-	-
	Freq Tested	0.458	-	-
	Gp x Freq Tested	0.544	-	-
	Freq Tested x Session	0.572	-	-
	Gp x Freq Tested x Session	0.550	-	-
Max Knee Angle Velocity	Session*	0.034	3.580	0.204
	Gp x Session	0.367	-	-
	Freq Tested	0.459	-	-
	Gp x Freq Tested	0.557	-	-
	Freq Tested x Session	0.133	-	-
	Gp x Freq Tested x Session	0.125	-	-
Mean Abs AoA	Session**	0.002	7.992	0.363
	Gp x Session	0.359	-	-
	Freq Tested†	0.062	4.114	0.227
	Gp x Freq Tested	0.669	-	-
	Freq Tested x Session	0.306	-	-
	Gp x Freq Tested x Session	0.340	-	-

* $p<0.05$, **$p<0.01$, † Approaching Significance at $p<0.05$

Maximum UUS Velocity

There were no statistically significant changes in max *U* across any of the testing sessions (Session: p= 0.132), there was also no significant interaction effect for Group x Frequency Tested x Session (p=0.238), or any other interaction tested. While no significant differences were established, there was a general trend in max *U* to decrease between the initial S0 session and the final RT session for both the Pref Freq and Imp Freq Tested in the PGp (see figure 5.1). The IGp also showed a decrease in the max *U* achieved at a Pref Freq between S0 and RT. However, max *U* achieved at the Imp Freq by the IGp, showed a slight increase between S0 and RT. The mean max *U* for all participants at both Freq Tested across all sessions was 1.19 $m.s^{-1}$ (± 0.12 $m.s^{-1}$). The slowest max *U* observed was 0.97 $m.s^{-1}$ and the fastest recorded was 1.51 $m.s^{-1}$ representing a 54% difference between the extreme values recorded.

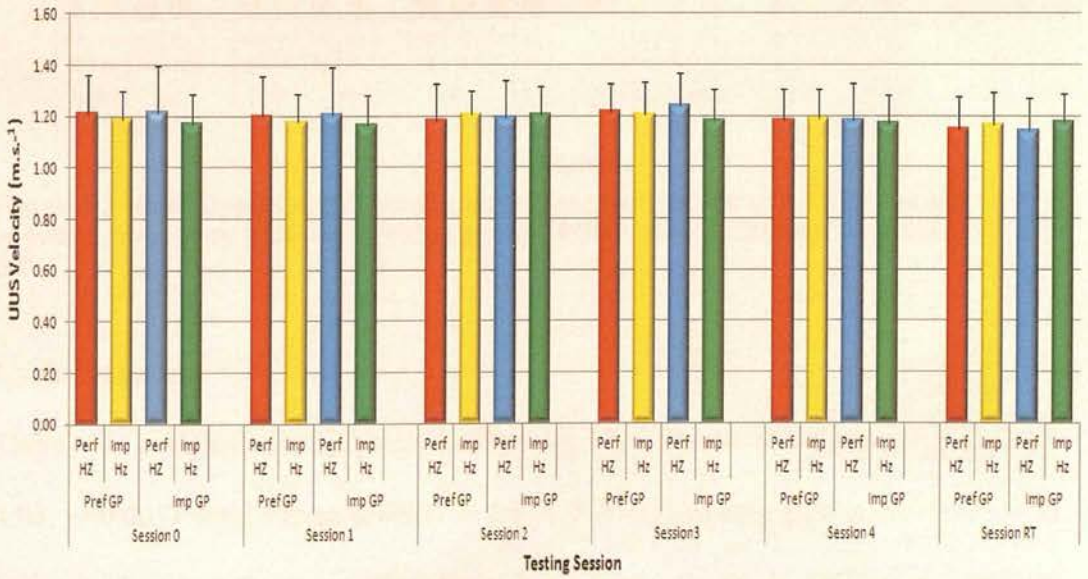


Figure 5.1 Mean maximal UUS Velocity across testing session (S0-S4 and RT) for preferred and imposed frequency, UUS by training group (PGp / IGp). Error bars represent sample S.D.

Cycle length

There was a statistically significant interaction effect for Freq Tested x Session ($F(2.36,10)=5.85$, $MSE= 608.317$, $p=0.005$), with a large effect size ($\eta_p^2 = 0.295$). There were significant differences ($p<0.05$) identified by Freq Tested between S3 and S4, and S3 and S5, with CL lower in the Pref Freq Tested across Session (except S3 and S4) irrespective of training group (see figure 5.2). There was no significant difference for Group x Frequency Tested x Session ($p=0.722$), or any other interaction tested.

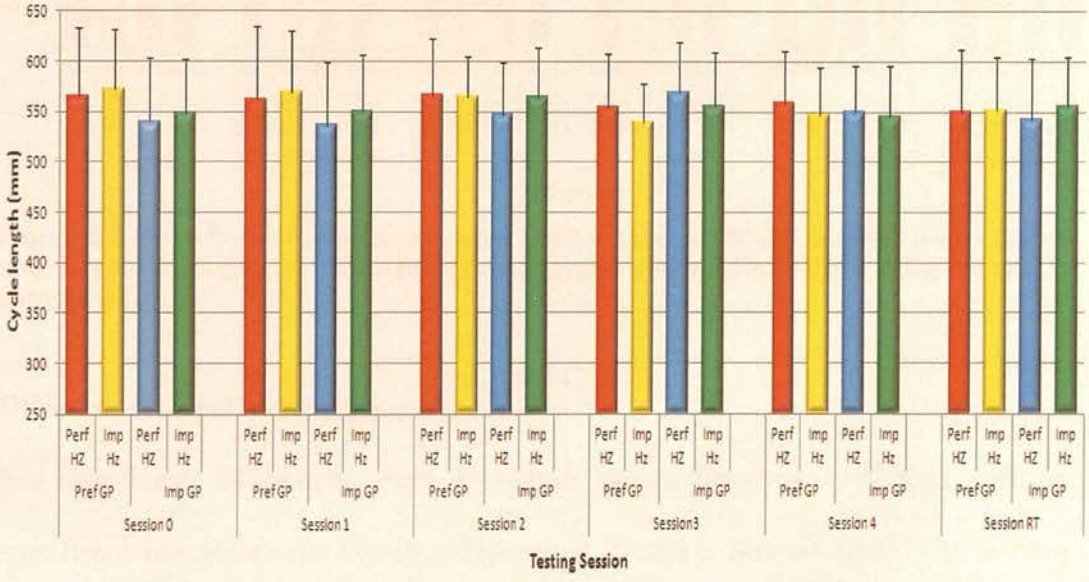


Figure 5.2 Mean Cycle Length across testing session (S0-S4 and RT) for preferred and imposed frequency UUS, by training group (PGp / IGp). Error bars represent sample S.D.

Cycle frequency

There was a significant interaction effect for Freq Tested x Session ($F(2.72,10) = 4.95$, $p=0.007$) with a large effect size ($\eta_p^2 = 0.261$), showing significant differences between the Pref Freq and Imp Freq Tested between both S0 and S1 and the remainder of the testing sessions. It can be seen from Figure 5.3 that the cycle frequencies are higher for Pref Freq Tested than Imp Freq Tested in S0 and S1 for both training groups. From S3 through to RT the mean values for Imp Freq Tested is

consistently higher in both training groups than that achieved in the Pref Freq Tested. There was no significant interaction for Group x Frequency Tested x Session (p=0.891) or any other interaction tested.

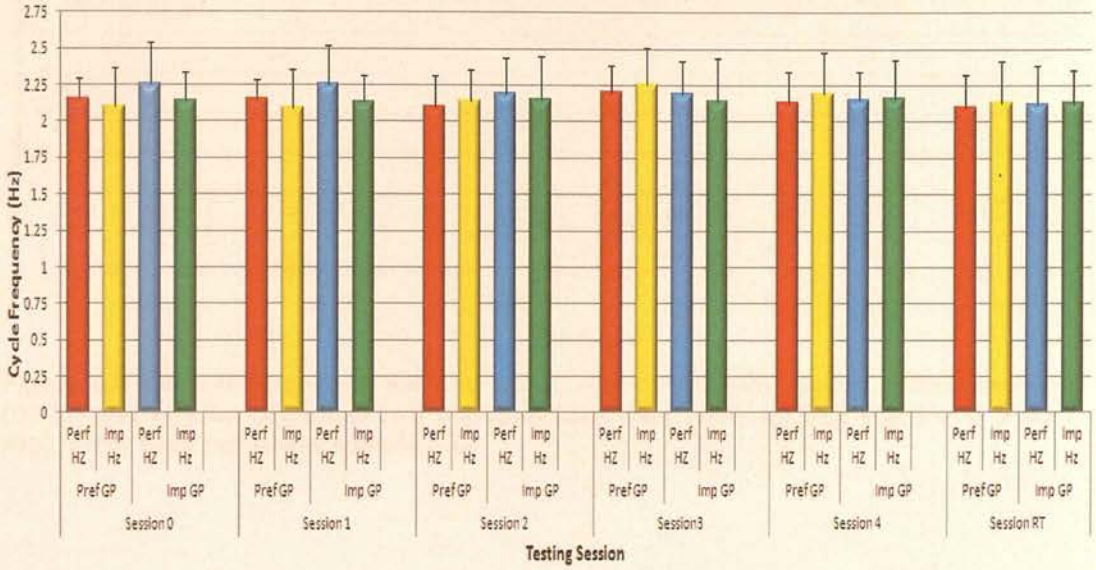


Figure 5.3 Mean Cycle Frequency across testing session (S0-S4 and RT) for preferred and imposed frequency UUS, by training group (PGp / IGp). Error bars represent sample S.D.

Difference in cycle frequency

No significant differences were identified across Sessions (p=0.462) and no significant interaction for Group x Frequency Tested x Session (p=0.788) or Freq Tested (p=0.938). Although the PGp showed no significant difference between sessions, there were increases in the variability (as denoted by the error bars - SD) for both the Pref Freq and Imp Freq Tested. The IGp showed an initial lower variability in the Pref Freq Tested, which then increased from S2 through to RT, while the Imp Freq Tested variability remained stable through S0-S3 and reduced in S4 an RT.

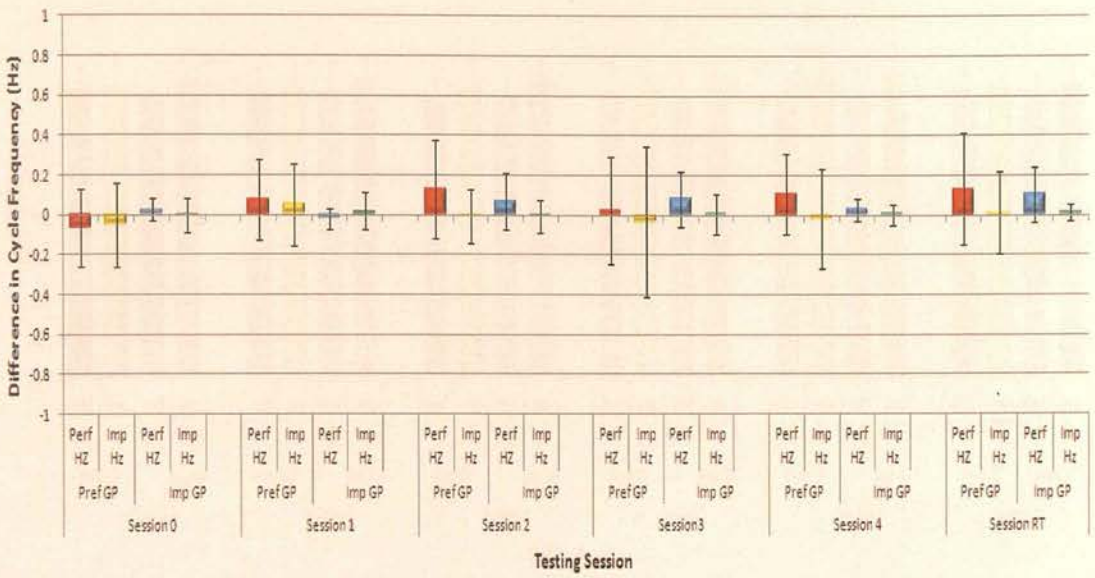


Figure 5.4 Mean difference in set and actual cycle frequency across testing session (S0-S4 and RT) for preferred and imposed frequency UUS, by training group (PGp / IGp). Error bars represent sample S.D.

Strouhal number

The *St* values showed no significant main effect foe Session (p= 0.711) or interaction effect for Group x Frequency Tested x Session (p= 0.882). However, the interaction effect for Group x Freq Tested was found to be approaching significance ($F(1,14)$= 3.22, p= 0.095) with a large effect-size statistic (η_p^2 = 0.187), with *St* number being consistently higher (mean difference = 0.05 ± 0.015) across all sessions, irrespective of training group, for the Imp Freq Tested (see figure 5.5). A higher *St* corresponds to lower UUS efficiency. There were no other statistically significant differences found for any other interactions

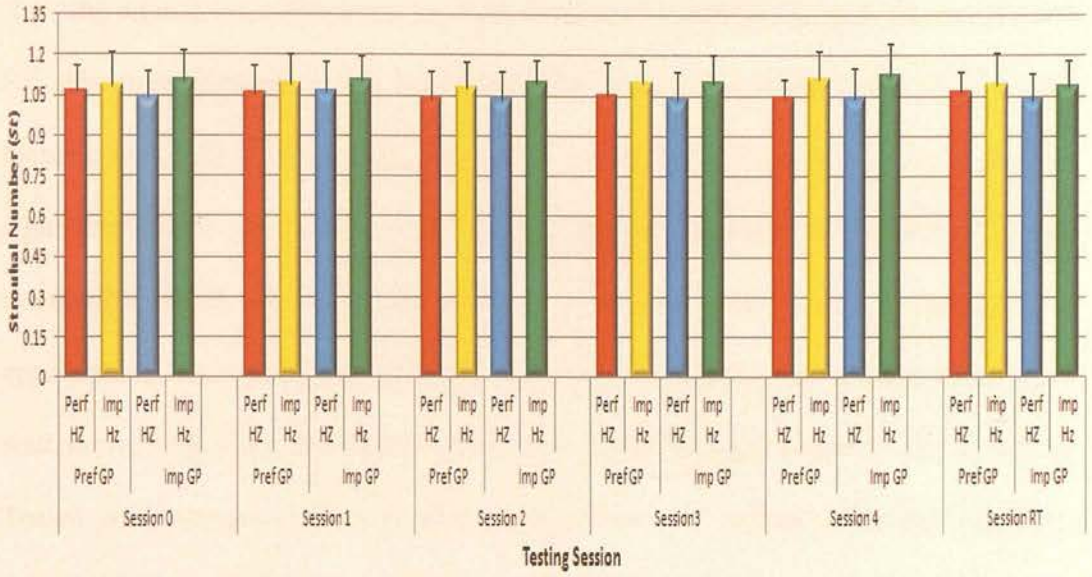


Figure 5.5 Mean Strouhal number across testing session (S0-S4 and RT) for preferred and imposed frequency UUS by training group (PGp / IGp). Error bars represent sample S.D.

Mean Absolute relative phase (MARP)

Heave v Pitch angle MARP

There was a significant main effect for Session ($F(2.06,10) = 32.06$, $p=0.001$) with a large effect-size statistic ($\eta_p^2 = 0.696$), showing a significant difference ($p<0.05$) between S0 and S2, S3, S4 and RT and also RT and S2, S3, and S4. The MARP Heave v Pitch angle increased in both Pref Freq and Imposed Freq Tested for both training groups, with mean MARP Heave v Pitch angle increasing from S0 (119.86°) through to S4 (124.52°) before dropping slightly in the RT session (123.97°). There were no significant differences found for Group x Frequency Tested x Session ($p=0.780$) any other interaction tested.

Foot v Thigh MARP

There was a significant difference for Session as a main effect ($F(2.67,10) = 6.01$, $p=0.003$) with a large effect-size statistic ($\eta_p^2 = 0.300$), with repeated contrasts

showing significant differences ($p<0.05$) between S2 and S3, S2 and S4, and S2 and RT. The mean Session values for MARP Foot v Thigh increased from S0 (238.96°) to peak at S3 (241.56°) before decreasing slightly at RT (240.63°). There was no significant difference for Group x Frequency Tested x Session ($p=0.496$) or any other interaction tested. However, the difference between Freq Tested x Session was approaching a significance ($F(5,10) = 2.311$, $p=0.059$) with a large effect-size statistic ($\eta_p^2 = 0.142$). The MARP for Foot v Thigh segment angle for the Pref Freq Tested was consistently lower (mean difference -3.15° ± 0.88) than the Imp Freq Tested within both the PGp and IGp. No significant differences we found for Freq Tested ($p=0.560$).

Propulsive wave velocity

Shoulder–hip propulsive wave velocity

Shoulder–hip propulsive wave velocity showed no significant difference identified for Group x Frequency Tested x Session ($p = 0.137$). No other significant effects were found.

Knee–ankle propulsive wave velocity

For the Knee–ankle propulsive wave velocity data there was a significant interaction effect for Freq Tested x Session ($F(2.28,10)=4.20$, $p=0.01$) with a large effect-size statistic ($\eta_p^2 = 0.231$). The initial values (S0) for Pref Freq Tested are slightly higher than Imp Freq Tested in both training groups (PGp +0.08 ms.$^{-1}$; IGp +0.21 ms.$^{-1}$), this relationship remains the same for S1. However, beyond S1 (S2-S4) the mean knee-ankle wave velocity values are higher in the Imp Freq Tested for both training groups (mean difference 0.06 ms.$^{-1}$), with RT mean values being almost equal across

Freq Tested and training groups. There was no significant interaction effect for Group x Frequency Tested x Session (p = 0.340) and no other significant effects were found. However, the difference between Session was approaching statistical significance ($F(2.28,10)=2.47$, $p=0.094$) with a large effect-size statistic (η_p^2 = 0.150).

Joint centre amplitudes and Joint ROM

Shoulder amplitude

The shoulder amplitude data was found to be significantly different for Freq Tested x Session ($F(5,10)$ = 2.48, $p=0.04$) with a medium effect-size statistic (η_p^2 = 0.150). The differences between Freq Tested at both S0 and RT were found to be significantly different ($p<0.05$) compared to the remainder of the sessions (S1-S4). Over the remaining sessions (S1-S3) the mean shoulder amplitude values changed in both the Pref Freq Tested and the Imp Freq Tested for both the PGp and IGp, with the shoulder amplitude becoming higher in the Imp Freq Tested (see figure 5.6). In S4 and RT the shoulder amplitude switches back with Pref Freq Tested values being larger. There was no significant interaction effect for Group x Frequency Tested x Session ($p=0.927$), or any other interactions tested.

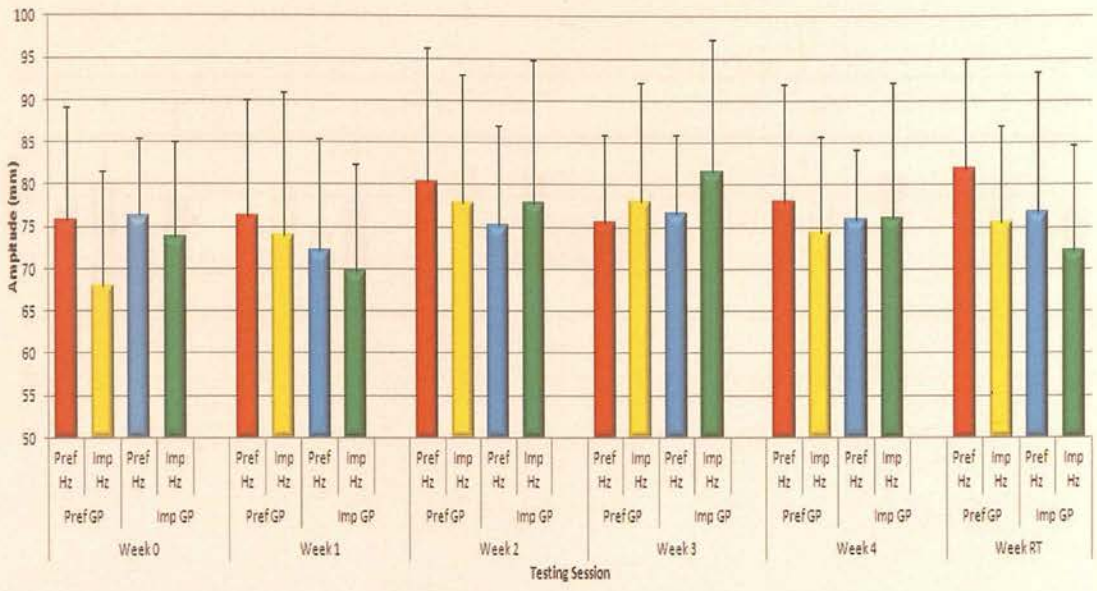


Figure 5.6 Mean Shoulder Amplitude across testing session (S0-S4 and RT) for preferred and imposed frequency UUS by training group (PGp / IGp). Error bars represent sample S.D.

Hip amplitude

There was a statistically significant interaction effect in hip amplitude for Freq Tested x Session ($F(5,10) = 3.67$, $p=0.005$) with a large effect-size statistic ($\eta_p^2 = 0.208$), showing a consistent statistically significant difference between the Pref Freq and Imp Freq Tested for all except RT. The hip amplitude values in the Imp Freq Tested were consistently higher (mean difference = 12.14 ± 3.52 mm) than those achieved in the Pref Freq Tested, with the exception of the values achieved in the RT (see figure 5.7). There was no statistically significant interaction effect in hip amplitude for Group x Frequency Tested x Session ($p=0.095$) or any other interaction tested.

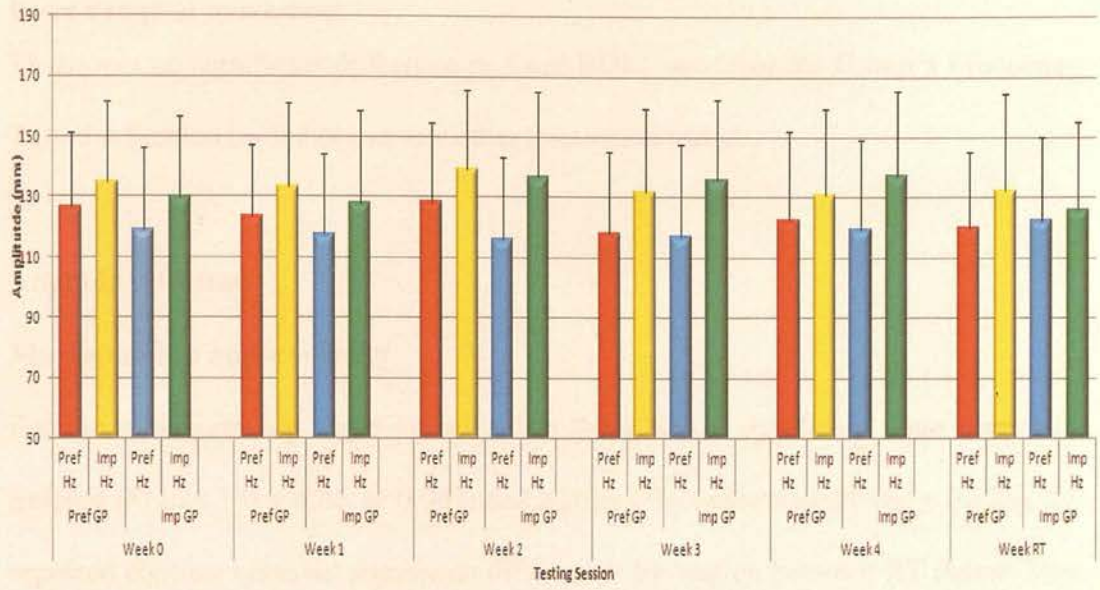


Figure 5.7 Mean Hip Amplitude across testing session (S0-S4 and RT) for preferred and imposed frequency UUS by training group (PGp / IGp). Error bars represent sample S.D.

Knee Amplitude

There was no significant changes in Knee amplitude for Group x Frequency Tested x Session ($p = 0.487$), or any other interaction tested.

5th MPJ amplitude

The 5th MPJ data was found to change significantly for Freq Tested x Session ($F(2.91,10) = 5.53$, $p=0.003$) with a large effect size statistic ($\eta_p^2 = 0.283$) with 5th MPJ amplitude consistently higher (mean difference = 30.42 ± 8.28 mm) across all sessions in the Imp Freq Tested with the exception of S3 (mean difference = 8.01 ± 8.28 mm) . There was no significant interaction effect for Group x Frequency Tested x Session ($p=0.779$) or any other interaction tested.

Knee range of movement

There was no significant difference in Knee ROM identified for Group x Frequency Tested x Session (p=0.324), or any other interaction tested.

Angular velocities

Maximum hip angle velocity

For the maximum hip angle velocity data there was a significant main effect for Session (F(2.24,10) = 6.68, p=0.003) and a large effect-size statistic (η_p^2 = 0.323), the repeated contrast revealed significant differences by session between RT (Mean Max Hip Velocity = 280.66 ± 8.24°s^{-1}) and all the previous sessions, with the exception of S1(Mean Max Hip Velocity = 299.09 ± 3.58°s^{-1}). The initial (S0) maximum hip angle velocity values for the Imp Freq Tested in the IGp were higher than their Pref Freq Tested and both the Pref and Imp Freq Tested in the PGp. The PGp maximum hip angle velocity at the Imp Freq Tested became consistently higher (mean difference = 9.84 ± 7.46 °.s^{-1}) than the values achieved at their Pref Freq Tested from S1 through to RT. With the exception of S1 the IGp had higher maximum hip angle velocity values in the Imp Freq Tested. The RT values showed significant decreases in both Freq Tested and in both training groups. There was no significant interaction effect found for Group x Frequency Tested x Session (p=0.550), or any other interaction tested.

Maximum knee angle velocity

Maximum knee angle velocity showed a statistically significant main effect for Session (F(2.27,10) = 3.85, p=0.034) with a large effect-size statistic (η_p^2 = 0.204), with repeated contrasts revealing significant differences (p<0.05) between S0

(724.14 ± 14.1 $^{\circ}s^{-1}$) and S1 (703.25 ± 19.39 $^{\circ}s^{-1}$) and between S4 (721.81 ± 11.60 $^{\circ}s^{-1}$) and RT (696.69 ± 7.98 $^{\circ}s^{-1}$). No significant interaction effect was found for Group x Frequency Tested x Session (p=0.125), or any other interaction tested.

Mean Absolute AoA

Mean Abs AoA data was found to have a significant main effect for Session $F(2.08,10) = 7.99$, p=0.002) with a large effect size statistic ($\eta_p^2 = 0.363$). Repeated contrasts revealed significant differences (p<0.05) between S1 (44.19 ± 0.31) and both S3 (45.59 ± 0.23) and S4 (44.59 ± 0.43) and for S2 (44.63 ± 0.66) and both S3 and S4, higher values for means Abs AoA in S3 and S4 across both Freq Tested and training groups. The AoA data was also approaching a statistically significant difference by Freq Tested ($F(1,14) = 4.11$, p=0.062) also with a large effect size statistic ($\eta_p^2 = 0.227$). There was a general increase in the disparity between the Freq Tested AoA values across the testing and training period for both PGp and IGp. No significant interaction effect for Group x Frequency Tested x Session (p=0.340) was found.

Continuous Relative Phase

Given the extent of the disparity evident in max U within this homogenous sample population of skilled age-group swimmers, exploring the extremes (fastest and slowest) offers some insight into the behaviours observed in response to the modality of training undertaken.

Foot v Shank CRP

Figure 5.8 shows the mean ensemble Foot v Shank CRP curves for the fastest and slowest underwater undulatory swimmers (as determined at S0) in each of the training groups (PGp and IGp) for both the Freq Tested. Each of the separate graphs contains the mean ensemble CRP curves of the separate session CRP data (S0-RT), with the point by point RMSE from S0 (as denoted by the error bars) included to show the initial levels of CRP variability. All of the participants included in figure 5.8 show similar mean CRP ensemble curves and also exhibit changes in their Foot v Shank CRP beyond the initial (S0) levels of variability at several time points within the kick cycle, in at least one of the subsequent testing sessions.

While there were changes in the Foot v Shank segment couplings between sessions, the within-subject Foot v Shank CRP temporal structure remained relatively consistent for all the data presented, with only slight changes in the scale of the relative phase observed between sessions. The majority of CRP deviation outside the initial S0 variability occurred in S3, S4 and RT for Pref Freq Tested (SW, BP and MS); and in S3 and S4 (MS), S3 and RT (SW) and S2-RT (BP and RH) for Imp Freq Tested.

Notably, the point by point RMSE variability observed in the fastest swimmers (SW and BP) was found to increase at the Imp Freq compared to Pref Freq Tested (at S0). Conversely, the point by point RMSE variability observed in the slowest swimmers (RH and MS) was found to decrease at the Imp Freq compared to Pref Freq Tested.

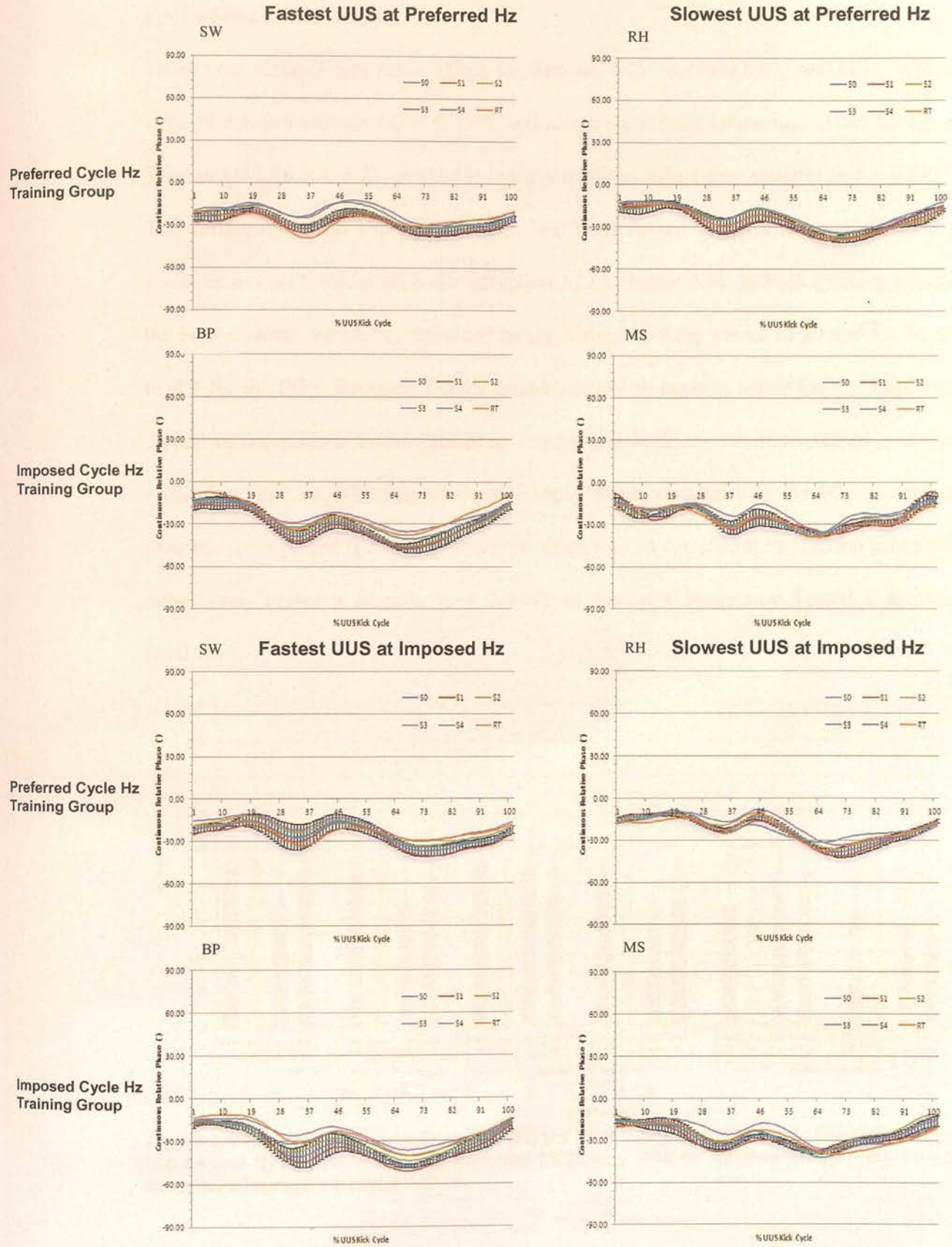


Figure 5.8 Foot v Shank CRP curves for preferred and imposed cycle frequencies from the fastest and slowest swimmers of the preferred and imposed training groups. Error bars represent point by point RMSE for Session 0.

Foot v Shank CRP RMSE

There was a significant main effect for Session ($F(2.36,10)=11.89$, $p<0.001$), with a large effect-size statistic ($\eta_p^2 = 0.459$), and also a significant interaction effect for Gp x Session ($F(2.36,10)=3.21$, $p=0.046$), with a medium effect-size statistic ($\eta_p^2 = 0.187$). The variability in the IGp (for Pref and Imp Freq Tested combined) was consistently lower across all sessions with the exception of S4 (figure 5.9). In both training groups the Foot v Shank variability remained larger in the Imp Freq Tested in S0 and S1. In S3 to RT for the PGp, the mean Foot v Shank variability became lower for the Imp Freq Tested in comparison to the Pref Freq Tested, and both consistently reduced over the remaining sessions. The magnitude of Foot v Shank variability in the IGp fluctuated over the same period (S3 –RT). However, there was no significant interaction effect for either Freq Tested x Session (p = 0.116), or Group x Frequency Tested x Session (p=0.708).

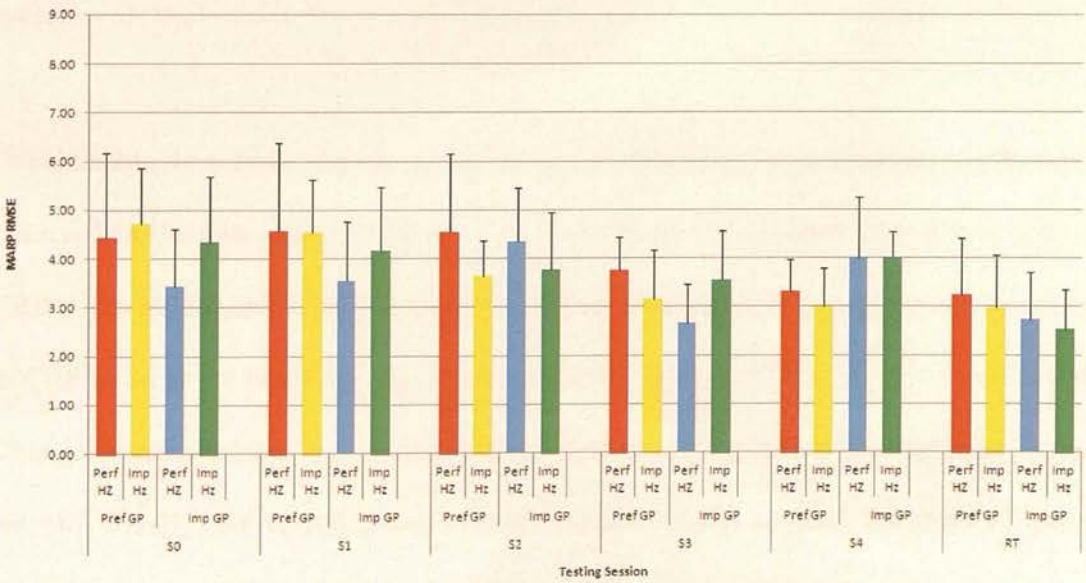


Figure 5.9 Root Mean Square Error (RMSE) for Foot v Shank CRP across testing session (S0-S4 and RT) for preferred and imposed frequency UUS by training group (PGp / IGp). Error bars represent sample S.D.

Shank v Thigh CRP

The point by point RMSE observed in the initial (S0) Shank v Thigh CRP showed higher levels of variability at the start/end of the UUS kick cycle in comparison to the remainder of the kick cycle, for all the participants Imp Freq Tested, and the majority of the Pref Freq Tested (with the exception of MS). There was reduced variability in Shank v Thigh CRP during the dorsal reversal point (approximately 19-65%) of kick cycle, in both fastest and slowest swimmers. The within-subject temporal structure of the CRP curves was similar across all the testing sessions for all participants shown in figure 5.10, with the exception of MS, whose Pref Freq Tested Shank v Thigh CRP showed a distinctly different segmental coupling pattern compared to their Shank v Thigh CRP at the Imp Freq Tested. The CRP curve for SW (the fastest UUS regardless of group) showed a slightly different CRP relationship than the remainder of those presented, with a greater change in relative phase occurring during the dorsal reversal point of the kick cycle.

Considerable deviations outside of the initial (S0) Shank v Thigh CRP variability were observed in the data shown if figure 5.10. Participant SW showed clear differences in CRP in the RT for both Pref and Imp Freq Tested. Participant RH demonstrated changes in CRP in S4 at the Pref Freq Tested and across S3, S4 and RT for the Imp Freq Tested. Changes were observed in S1 for Pref Freq Tested and the RT in the Imp Freq Tested for MS. Finally, BP demonstrated changes outside of the original S0 point by point RMSE at the dorsal reversal point across S1-RT in both the Pref and Imp Freq Tested.

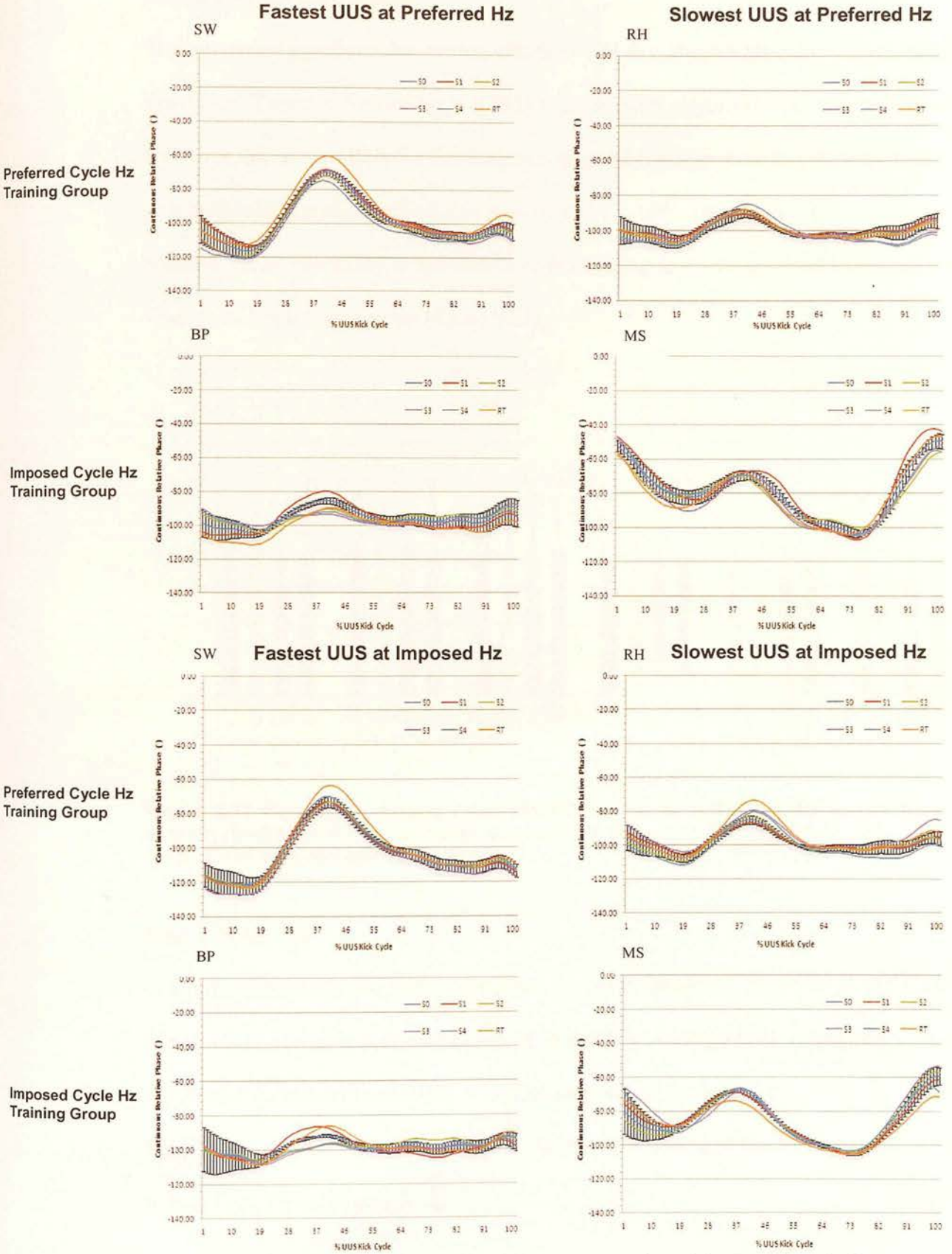


Figure 5.10 Shank vs Thigh CRP curves for preferred and imposed cycle frequencies from the fastest and slowest swimmers of the preferred and imposed training groups. . Error bars represent point by point RMSE for Session 0.

Shank v Thigh CRP RMSE

There were no significant interaction effects in Shank v Thigh RMSE for either Group x Frequency Tested x Session (p = 0.751) and no other significant effects were found. However, the main effect for Session was approaching significance (F(2.64,10)=2.45, p=0.086) with a medium effect-size statistic (η_p^2 = 0.149). There was a general trend for Shank v Thigh variability to decrease over the training and testing period irrespective of Freq Tested or training group (figure 5.11).

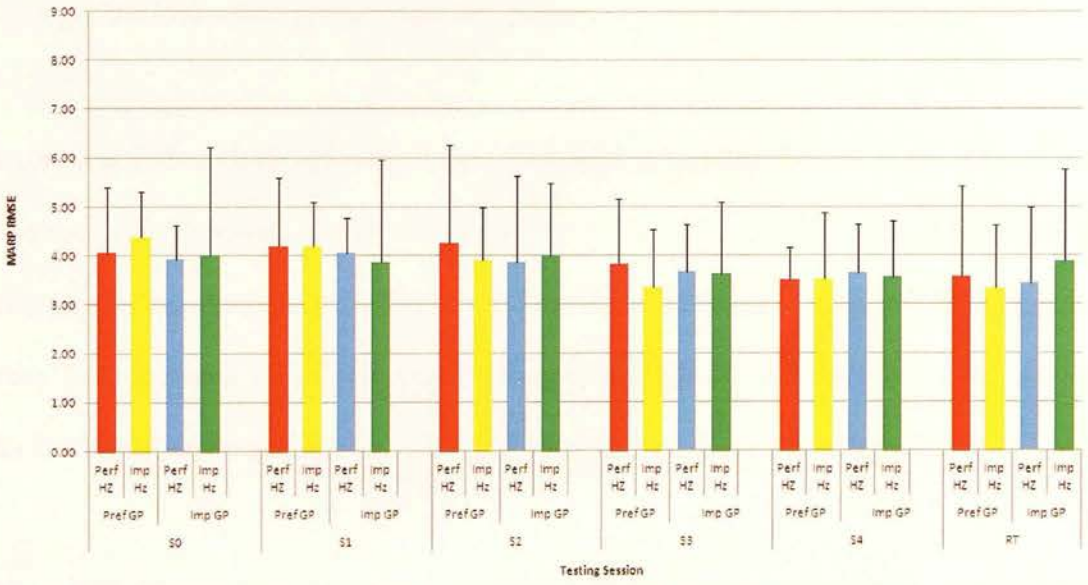


Figure 5.11 Root Mean Square Error (RMSE) for Shank v Thigh CRP across testing session (S0-S4 and RT) for preferred and imposed frequency UUS by training group (PGp / IGp). Error bars represent sample S.D.

Foot v Thigh CRP

A similar pattern for the initial (S0) point by point variability observed in the Foot v Shank CRP couplings was also observed in the Foot v Thigh CRP relationships, with the fastest swimmers' variability found to increase at the Imp Freq compared to Pref Freq Tested and the slowest swimmers' variability reducing at the Imp Freq compared to Pref Freq Tested (figure 5.12).

Particpant SW showed changes in CRP outside the initial (S0) point by point variability for both S3 and RT during the latter two thirds of the kick cycle for the Pref Freq Tested and at RT during the final 50% and for S1, S2 and S3 during the final 25% of the kick cycle in the Imp Freq Tested. Participant BP showed changes in CRP for the Pref Freq Tested during S1-S4 over the first 30% of the kick cycle and in S4, S5 and RT for the portion of the kick cycle immediatly following the dorsal reversal point. In addition, BP showed changes in CRP across all subsequent sessions (S1-RT) at various points throught the kick cycle for the Imp Freq Tested.

There was a clear deviation away from the initial CRP pattern for RH in S4 at the dorsal reversal point (between approx 19% and 65% of the kick cycle) at the Pref Freq Tested and much clear deviations for S1, S2, S4 and RT for the same time period in the Imp Freq Tested. There were deviations throughout the kick cycle for MS in S1-S3 and RT for the Pref Freq Tested and S2 , S3 and RT for the Imp Freq Tested.

Also, MS (the slowest swimmer regardless of training group) again demonstrated a distinctly different segmental coupling pattern for their Foot v Thigh CRP at the Pref Freq Tested compared to that achieved at the Imp Freq Tested.

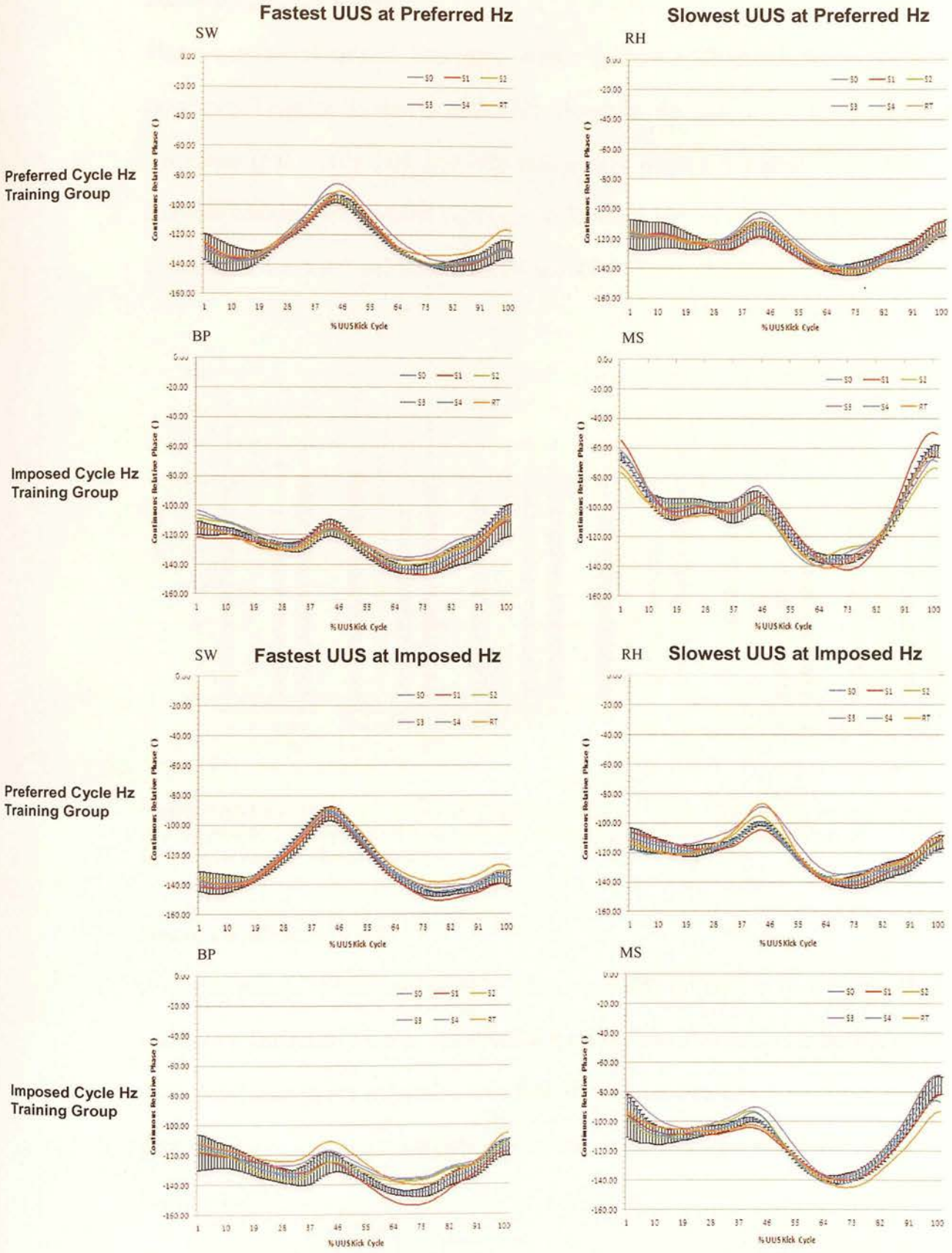


Figure 5.12 Foot v Thigh CRP curves for preferred and imposed cycle frequencies from the fastest and slowest swimmers of the preferred and imposed training groups. Error bars represent point by point RMSE for Session 0.

Foot v Thigh CRP RMSE

There were no significant interaction effects in Foot v Thigh RMSE for Group x Frequency Tested x Session (p = 0. 282). However, the main effect for Session was significant (F(2.93,10)=5.04, p=0.005) with a large effect-size statistic (η_p^2 = 0. 265). Pairwise comparisons revealed significant differences between S0 and S3, S4 and RT, S1 and S3, S4 and RT, and S2 and S3, S4 and RT.

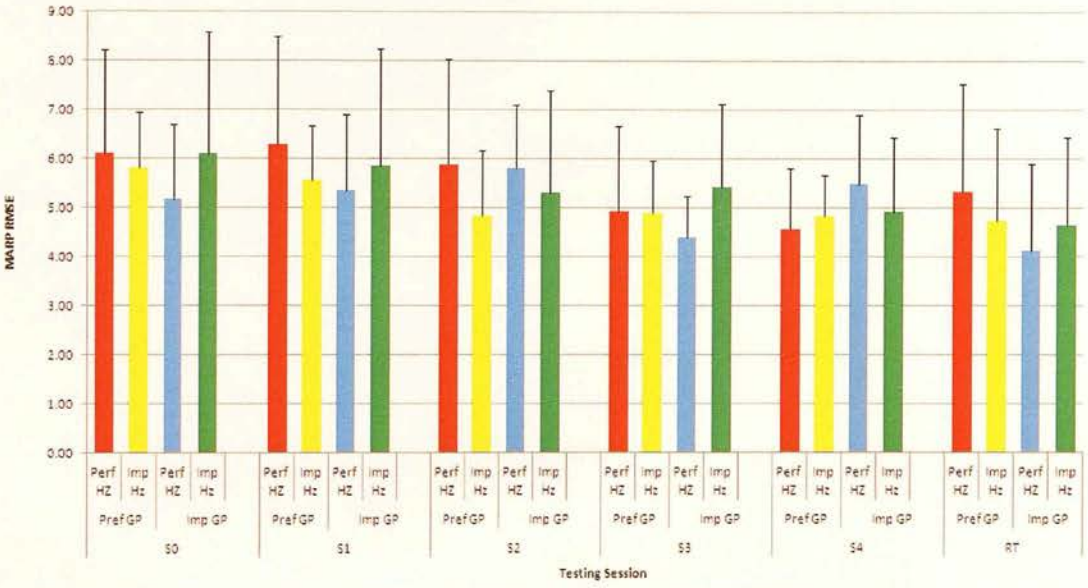


Figure 5.13 Root Mean Square Error (RMSE) for Foot v Thigh CRP across testing session (S0-S4 and RT) for preferred and imposed frequency UUS by training group (PGp / IGp). Error bars represent sample S.D.

Heave v Pitch angle CRP

A similar pattern of increased point by point variability (as seen in both Foot v Shank and Foot v Thigh CRP) can be observed for both the fastest swimmers in the initial (S0) Imp Freq Tested in comparison to their Pref Freq Tested (see figure 5.14). Conversely, decreased point by point variability was evident for the slowest swimmers at the Imp Freq Tested.

While the CRP values achieved by any of the participants do not meet the 75 degree optimal relative phase relationships for thrust production (Anderson *et al.*, 1998) the fastest swimmers showed the relative phase to consistently decrease at two similar time points (start/end of the dorsal reversal point).

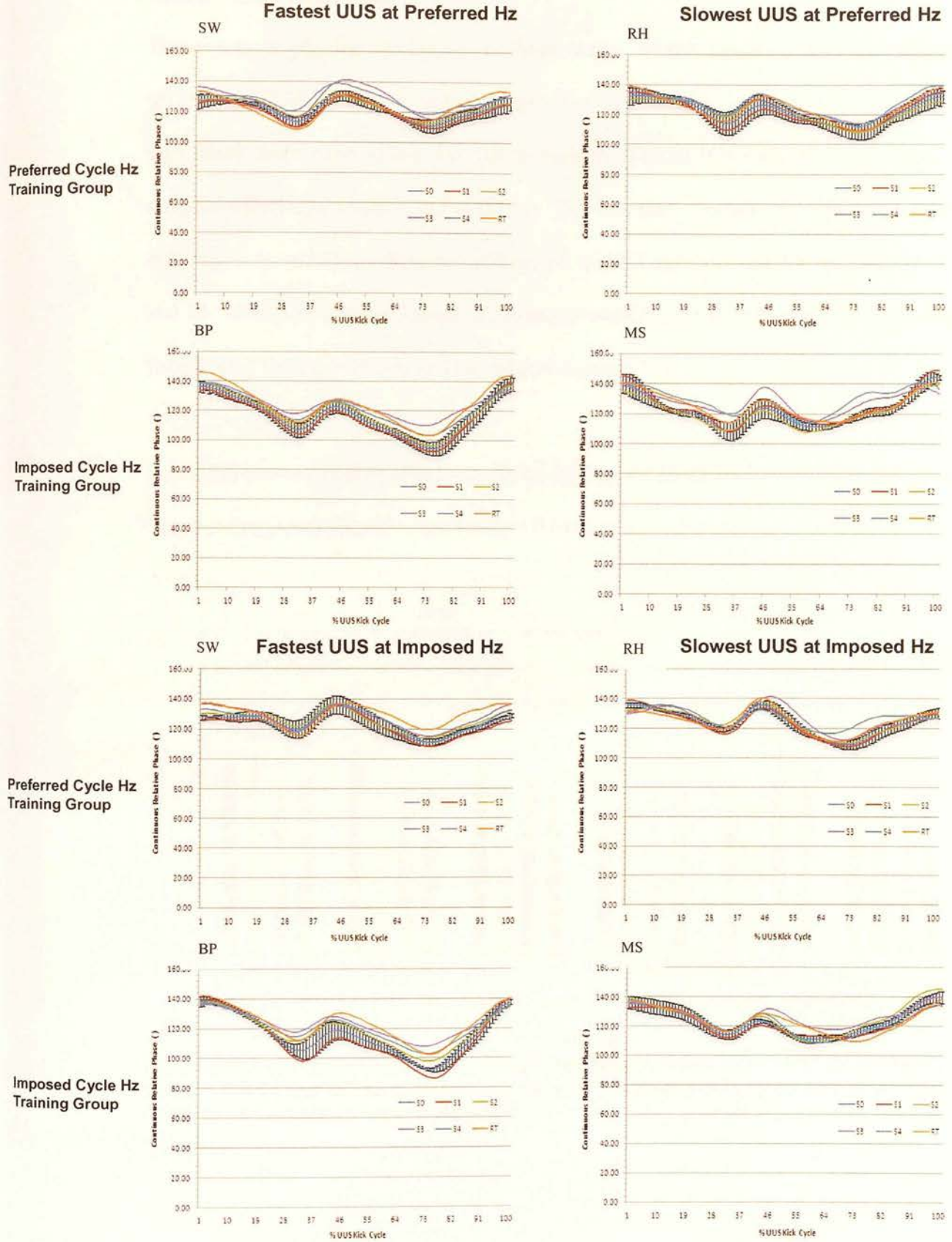


Figure 5.14 Heave v Pitch angle CRP for preferred and imposed cycle frequencies from the fastest and slowest swimmers of the preferred and imposed training groups. Error bars represent point by point RMSE for Session 0.

Heave v Pitch angle CRP RMSE

There was a significant Heave v Pitch angle RMSE main effect for Session ($F(2.88,10)=7.90$, $p=0.001$), with a large effect-size statistic ($\eta_p^2 = 0.361$) and also a significant interaction effect for Gp x Session ($F(2.88,10)=3.41$, $p=0.028$) with a medium effect-size statistic ($\eta_p^2 = 0.196$). The repeated contrasts revealed significant differences ($p<0.05$), by Session between S0 and S3 and between RT and S0, S1, S2 and S3. There was a general trend of decreased variability in both the Pref Freq and Imp Freq Tested for the PGp across S1 to S4 (see figure 5.15).

No significant interaction effect was found in Heave v Pitch angle variability for either Group x Frequency Tested x Session ($p = 0.618$) or any other effect.

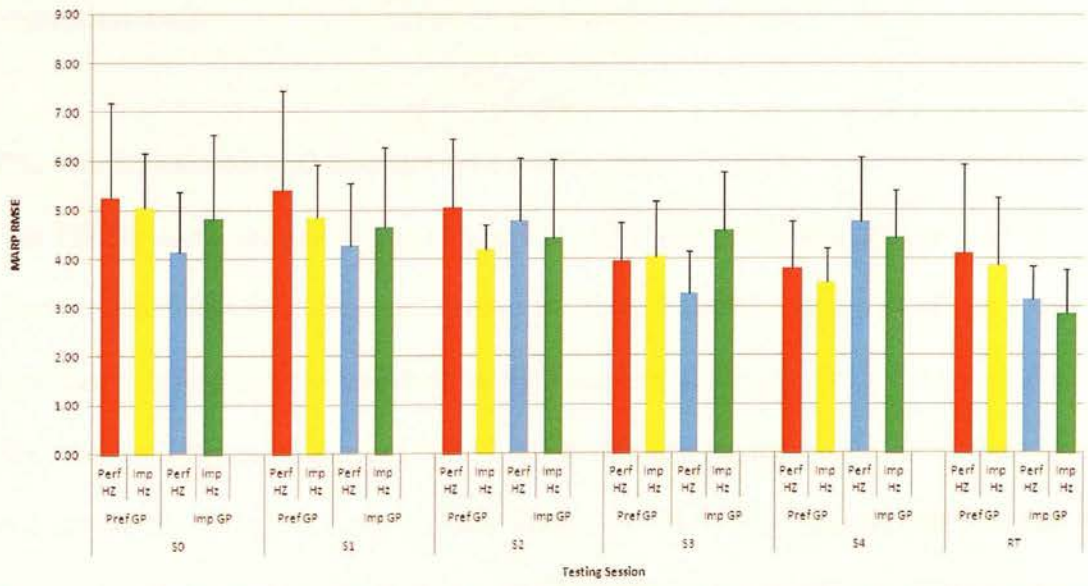


Figure 5.15 Root Mean Square Error (RMSE) for Heave v Pitch angle CRP across testing session (S0-S4 and RT) for preferred and imposed frequency UUS by training group (PGp / IGp). Error bars represent sample S.D.

5.4 Discussion

The purpose of this study was to investigate the effects of training at an imposed preferred cycle frequency for improving maximal UUS performance in skilled age-group swimmers. To this end four specific aims were addressed: (1) to compare the effects of training at a preferred cycle frequency and an imposed (preferred) cycle frequency, on the kinematics and measures of coordination of UUS in skilled age-group swimmers, (2) to establish the efficacy of using the measured coordinative structures as an order parameter to encapsulate the USS system dynamics, (3) to determine the efficacy of imposed cycle frequency training for promoting learning and adaptation in both the local and global UUS system dynamics, (4) examine the act of frequency imposition to determine its effects on performance and coordination to enable future studies delineate the effects of changing cycle frequency from the act imposition itself.

Discrete kinematics and measures of coordination

The results from the initial three–way RM ANOVA performed for each of the discrete kinematic variables and measures of coordination analysed showed no significant differences were evident for the complete model (Group x Freq Tested x Session) in all fifteen variables (Table 5.2). In addition, no significant main effect or interaction for Group (Group x Freq Tested or Group x Session) were found. Training at an imposed cycle frequency had no statistically significant effect on any of the discrete kinematic variables or discrete measures of coordination in either of the two Freq Tested and/or across the training and testing period. In addition, no other statistically significant main effects or interactions were observed in six (max *U*, Freq difference, Strouhal number, shoulder–hip wave velocity, knee amplitude or,

knee ROM) out of the seventeen variables analysed with the RM ANOVA models (Table 5.2).

As stated, irrespective of training group, max *U*, the fundamental measure of UUS performance, was found not to differ between Group, Freq Tested or by Session. The max *U* values reported (mean max *U*= 1.19±0.12m.s^{-1}) within the present study are similar to those reported for national standard age-group swimmers (mean max *U*= 1.15m.s^{-1}) by Arellano *et al.* (2002). Results showed no significant difference in max *U* across the four weeks training period or after the two weeks retention period. Therefore, irrespective of training group the UUS training undertaken was ineffective for producing an improvement in max *U* in UUS. However, while the max *U* did not change significantly at either of the frequencies tested (Freq Tested) over the prescribed training and testing period, the manner in which max *U* was achieved was shown to alter (variations in CL and Hz) by Freq Tested x Session.

Knowing the relationship between max *U*, EE_Hz and CL (max *U* = EE_Hz x CL) and understanding that if max *U* does not change, then either both CL and EE_Hz values must remain the same or their respective values must vary by a proportional amount; then for statistical differences to be found (Freq Tested x Session) in both CL (p=0.005) and EE_Hz (p=0.007) then both modalities of training produced some adaptation to UUS. The initial higher CL values occurring at an Imp Freq Tested irrespective of training group, reduced in comparison to the CL values achieved at Pref Freq Tested over the S0 to S3 period (figure 5.2), with the mean CL values increasing at the Pref Freq Tested in both training groups. By S4 through to RT, the magnitude of disparity between the CL values achieved for both groups at both Freq

Tested reduced with similar mean CL values achieved. Given that there were no changes in max *U* and the stated changes occurring in CL, there was an expected concomitant change in EE_Hz in direct relation to the CL values produced.

The initial disparity between the EE_Hz showed a higher EE_Hz value for the preferred Freq Tested up until S3 (figure 5.3) when the disparity between EE_Hz values became much less at both Freq Tested. The Freq Differences values (figure 5.4) representing the difference in the EE_Hz achieved in relation to the individual baseline mean preferred EE_Hz, showed the consistency with which the IGp achieved their cycle frequency at both Pref and Imp Freq Tested. The IGp was less variable and closer to the initial baseline preferred EE_Hz throughout the training and testing period. The PGp showed higher levels of variability throughout, and variability increased from S0 to S3. The results presented in figure 5.4 indicated that the IGp had reduced variability around a more stable cycle EE_Hz when compared to the PGp.

The EE_Hz values found within the current study (mean EE_Hz = 2.16 ± 0.22 Hz) are greater than those reported for national age-group swimmers by Arellano *et al.* (2002). The EE_Hz values from the current study more closely match the EE_Hz of collegiate swimmers (EE_Hz = 2.11Hz) from Connaboy *et al.* (2007a) or the international level swimmers (mean EE_Hz = 2.14 Hz) analysed by Arellano *et al.* (2002). These values are considerably less than those reported by Lyttle *et al.* (2004) for a single 'elite' swimmer performing at a higher velocity (max *U* = 2.13 - 2.16 $m.s^{-1}$) either at large amplitude/slow kick (EE_Hz = 2.27 Hz) or a small amplitude/fast kick (EE_Hz = 2.63Hz). Lyttle *et al.* (2004) analysed two different

type of UUS kick - fast (2.63 Hz) and slow (2.27 Hz) which resulted in max *U* of 2.16 $m.s^{-1}$ and 2.13 $m.s^{-1}$ respectively, suggesting that similar to the present study CL must have increased with a slow kick to maintain similar levels of max *U*.

The results of the present study indicated that it was the initial constraint of the Imp Freq Tested which influenced EE_Hz and CL and not the training group condition which had no effect over the training and testing period. The initial higher CL at the Imp Freq Tested in both groups indicated that irrespective of training modality the act of imposing a cycle frequency initially resulted in the swimmers utilising larger CL in response to the relatively lower EE_Hz achieved at the Imp Freq Tested compared to the Pref Freq Tested, in order to maintain max *U*. The mechanism by which the initially higher CL values were attained at an Imp Freq Tested will be examined as the remaining variables are discussed.

The analysis of the data for max *U*, CL, EE_Hz and Freq Diff demonstrates that the imposed frequency training was ineffective in producing notable changes in these fundamental aspects of UUS performance. While there were differences between the Freq Tested across the testing Sessions for CL and EE_Hz, ultimately none of these were sufficient enough to result in a statistically significant change in max *U* either for Freq Tested or by training group.

Similar to EE_Hz and CL, several other variables (knee-ankle wave, shoulder amplitude, hip amplitude and 5^{th} MPJ amplitude) were found to be significantly different by Freq Tested x Session (MARP Foot v Thigh was approaching significance at p=0.059). The differences found for the Freq Tested x Session

interaction showed that irrespective of the training group (PGp/IGp) the values attained at the respective Freq Tested were found to be statistically significant at various time points across the testing and training period. For example, initial disparities in magnitude were observed in both knee-ankle wave velocity and shoulder amplitude at S0, between the values obtained at a Pref Freq Tested and the Imp Freq Tested. This disparity was found to reduce after S3, with similar values attained for both Freq Tested for S4 and RT. For hip amplitude the initial disparity between the amplitude achieved at the Pref Freq Tested and the Imp Freq Tested remained throughout the training and testing period. However, the magnitude of the disparity in hip amplitude between the Freq Tested was found to change within the final (RT) session. This demonstrated that the magnitude of some of the respective variables, at the two Freq Tested, became similar as a consequence of the UUS training and/or repeated testing, irrespective of training group.

A number of other discrete variables (MARP Heave v Pitch angle, MARP Foot v Thigh, max hip angle velocity, max knee angle velocity and mean Abs AoA) were significantly different between Sessions (with knee ankle wave velocity approaching sig. at p=0.094) demonstrating that irrespective of training group and Freq Tested, changes in these variables occurred across the training and testing period. Again, highlighting that while max U was not found to change across the training and testing period the manner in which it was achieved did alter. This further suggests that it is the initial constraint imposed by the Imp Freq Tested which may have influenced these variables, and not the training group condition which had less influence over the training and testing period.

One variable (*St*) was approaching significance (p=0.095) for a Group x Freq Tested interaction effect. The mean *St* for Pref Freq Tested (*St* = 1.05 ± 0.014) and Imp Freq Tested (*St* = 1.10 ± 0.012) is representative of the discrepancy between the values across all the testing sessions. The *St* was consistently higher at the Imp Freq Tested in all testing sessions (S0-RT), which would indicate reduced efficiency at the Imp Freq Tested, irrespective of training group. Therefore, the reason for the *nearly* significant difference for the Group x Freq Tested interaction is due to the differences in *St* values achieved at the Pref Freq Tested by the respective training groups. Interpreting these results also suggests that the ability to make the UUS performance more efficient at either of the Freq Tested was not achieved via the imposed or preferred cycle frequency training. The values of *St* within the present study were much higher than those achieved for aquatic animals (*St* ranging from 0.24-0.35) (Fish and Rohr, 2004), and slightly higher than those achieved by international swimmers (n=19; *St* = 0.79) reported by Arellano *et al.* (2002). The *St* values from the present study were similar to those achieved by the national age groups swimmers (n=13; *St*=0.95), within the study by Arellano *et al.* (2002). The *St* values achieved by the present sample population were higher than the 0.25-0.40 range reported as providing the most efficient UUS performance (Streitlien and Triantafyllou, 1998). The high *St* achieved at both Freq Tested are a clear demonstration of the short lived requirement for a maximal propulsive impulse at the expensive of propulsive efficiency.

The AoA, which provides an indication of the hydrodynamic performance and efficiency of the swimming body, was found to be approaching statistical significance for Freq Tested with the mean Abs AoA for the Pref Freq Tested

(44.67°±0.71°) being lower than the mean Abs AoA for the Imp Freq Tested (45.12°±0.52°). Again, similar to the data presented in study 2, the AoA data from the present study was outside the 15°-25° range suggested for optimal thrust production (Sfakiotakis *et al.*, 1999; Videler and Kamermans, 1985; Triantafyllou *et al.*, 1993). However, the representation of AoA as a discrete variable does not fully explain its behaviour and relevance to UUS performance. The maintenance of a positive AoA enables thrust to be produced throughout a larger proportion of the stroke cycle (Fish and Rohr, 1999; Lighthill, 1969; Videler and Kamermans, 1985). However, the AoA disparity reported only provides the mean values and does not reveal the extent to which a positive AoA is maintained. As stated in Study 2, the associated benefits of maintaining AoA within the hydro-dynamically derived optimal range may (1) simply not be possible as a consequence of the restricted morphology of humans, (2) only achievable within certain section(s) of the kick cycle, or (3) be sacrificed as a consequence of other factors i.e. propulsion optimised with respect to a different cost function, namely the recapturing of vortices (Study 2). However, further computational fluid dynamics research is required to confirm the validity of these assertions.

Before moving on to discuss the key aspects of coordination in relation to the training modalities employed, it is worth noting that while no statistically significant results were observed by group, this may have been as a consequence of the statistical methods employed. The use of Bonferroni corrections to minimise the chance of type I error, while effective, is a very conservative approach and may have resulted in values being rejected as significant as a consequence of the loss of statistical power (Field, 2000). The relatively small sample population within the

present study (n =16) may have also limited the identification of worthwhile differences that occurred; a consequence of the increased risk of a type II error (Field, 2000; Hopkins, 2000).

Discrete measures of coordination - MARP

The two discrete measures of coordination (MARP) for Foot v Thigh and Heave v Pitch angle previously identified as key determinants of UUS performance (Study 2) were observed to change as a consequence of the UUS training undertaken. Both discrete measures of coordination were identified to be statistically different ($p<0.05$) by Session. Therefore, irrespective of the modality of training undertaken or the Freq Tested the coordination was found to alter (statistically) across the testing and training period. The absence of a statistically significant difference by training group suggests that the effect of training undertaken by the IGp was no different to that of the PGp.

Changes in the MARP and increased MARP RMSE can be considered indicative of a perturbation to the movement system (e.g. change in a control parameter / task constraint), with the movement system exploring the action boundaries in an attempt to find appropriate solutions to the newly formed movement equation/constrained optimisation problem. Consequently, an increase in variability may indicate a willingness of the movement system to shift away from an established (previously stable) coordination pattern to a 'new' stable coordination pattern (Kurz and Stergiou, 2004).

Interpretation of the significance of the statistically identified changes in coordination (as represented by MARP) requires careful consideration. Interpretation of a statistically significant change in MARP as being representative of a sudden nonlinear change (bifurcation) from one coordinative state to another, in response to the imposed training (PGp/IGp) constraint, is an oversimplification of both the data and behaviour observed. As previously highlighted, the generic mechanisms of stability and variability are universal to all instances of phase transitions and / or pattern formations, with temporary increases in variability as a consequence of loss of stability within the attractor state (Kelso, 1994; Schloz, Kelso and Schoner, 1987).

However, Handford *et al.* (1997) suggest that the evolution of behaviour towards a more task specific state may not always be represented by an abrupt change, rather a re-scaling of an already established coordinative structure. Therefore, the use of a discrete measure of a coordinative structure should not be viewed in isolation when examining these changes in system dynamics, as the variability and stability of a coordinative structure has to be considered and the single mean value may mask any re-scaling apparent. Also, the use of discrete MARP data as being representative of the behaviour of the coordinative structure within a kick cycle has previously been questioned, as the single value does not reveal all the organisation and subtleties contained within the behaviour of a coordinative structure (Kurz and Stergiou, 2004). Therefore, the MARP data must be discussed in relation to its own variability/stability, and also the CRP data and their variability/stability.

Variability and stability of MARP (RMSE)

Whilst no statistically significant differences were found between the PGp and IGp in any of the discrete kinematics or discrete measures of coordination, the MARP RMSE of two coordinative structures were found to be significantly different for the two training groups. The MARP RMSE of both Foot v Shank and Heave v Pitch angle were observed to change significantly for the Group x Session interaction. Figures 5.9 and 5.13 showed the initial higher variability in the PGp (compared to the IGp) reducing, while the IGp MARP RMSE values remained relatively consistent across Sessions.

The MARP RMSE in three (Foot v Shank, Foot v Thigh and Heave v Pitch angle) out of the four coordinative structures analysed was also found to change significantly ($p<0.01$) by Session. The fourth coordinative structure (Shank v Thigh) was approaching significance ($p=0.086$) by Session. This reduction in variability (MARP RMSE) would have an impact on the probability of finding statistically significant results between Sessions for the MARP values of the respective coordinative structures. The reduction in variability occurring as a consequence of UUS training or exposure to the imposed frequency (PGp learning to adapt to the imposed Freq Tested with minimal exposure) would potentially enable smaller differences/changes in MARP to be identified as statistically significant. Therefore, the statistically significant changes which occurred in both Foot v Shank and Heave v Pitch angle MARP may not represent practically significant adaptations in the UUS system dynamics. Turvey (1990) suggested that the variability inherent in biological system can be seen as functional, allowing flexibility in the system dynamics to meet subtle changes in the task. Consequently, the variation observed in the Foot v Shank

and Heave v Pitch angle MARP which resulted in a statistically significant change may actually reflect the variability inherent within abundant active degrees of freedom available to form locally stable task dependent coordinative structures (Kulger and Turvey, 1987; Turvey, 1990).

Further support for this suggestion is provided from the respective MARP RMSE data, as the temporary loss of stability and increased variability associated with a transition to a new pattern of behaviour (Kelso, 1994); Schloz *et al.* 1987) are not apparent within the MARP RMSE data presented. However, the analysis of variability (MARP RMSE) and its stability presented within this study (variability changing between Sessions) was also limited as the stability of the coordinative structures was inferred from the changes in variability and not directly measured. Traditionally, the stability of an attractor state is measured via perturbation of the movement system by manipulation of a control variable and then examining the critical fluctuations and time required to return to the initial attractor state (relaxation time) once the perturbation has been removed (Kelso *et al.,* 1986).

While the MARP, MARP RMSE and CRP data from the present study can be analysed and discussed in relation to a more global understanding of critical fluctuations in coordinative state (change in variability over sessions), no measure of relaxation time was recorded. The nature of UUS prevented relaxation time from being assessed, as a consequence of the limited time swimmers are able to hold their breath and perform maximal UUS. Nonetheless, further exploration and discussion of the continuous data is required before confirming or refuting the claim that no

practically significant changes in coordinative state occurred in the coordinative structures measured.

Continuous measures of coordination - CRP

The presentation of CRP ensemble curves of the fastest and slowest UUS from both training groups (PGp / IGp) for both the Pref Freq and Imp Freq Tested provides an opportunity to examine the extremes of behaviours within this reportedly homogenous sample.

The CRP for the four coordinative structures measured all showed a number of the participants to deviate away from the initial S0 CRP values, with mean Session CRP ensemble curves shifting outside of the initial (S0) point by point RMSE at certain points throughout the kick cycle across sessions. These deviations suggest that these coordinative structures are altering as a consequence of the training undertaken (irrespective of training group). The minor deviations away from the established, initial coordinative state, which occur at specific points within the kick cycle represent a re-scaling of the already established coordinative state. As the participants within the present study are all skilled age-group swimmers with several years experience, the entrained, task specific, highly stable attractor states which have evolved to produce maximal UUS performance may be hard to shift away from (Clark and Philips, 1992; Thelen, 1995).

Moreover, Delignieres *et al.* (1998) suggested that even in beginners the stability of the initial attractor states for both frequency and phase relationships observed reveals that the intrinsic dynamics of a movement system can be difficult to overcome.

Therefore, given the general trend for max U to decrease slightly across the training and testing period, it may be suggested that while the training intervention has prompted a search of the perceptual-motor workspace, it has not achieved the goal of perturbing the system away from the established coordinative state to a higher order, more task specific and ultimately more successful coordinative state(s). Given that for none of the participants included in the CRP figures (5.6, 5.8, 5.10 and 5.12) max U changed noticeably (± 0.02 $m.s^{-1}$) over the training and testing period then the re-scaling apparent with their CRP data did not represent a practically significant change in coordinative state.

Also, with no change in max U observed in either of the training modalities employed for the different groups then it may be that the initial preferred EE_Hz determined during the baseline testing session cannot be exploited any further by employing training at a preferred frequency (either self selected or imposed) to reap any more performance benefits and/or that training at the preferred frequency limits exploration of the UUS system dynamics. As suggested by Glazier *et al.* (2003), functionally preferred highly stable coordination or 'attractor states' evolve and develop to enable and sustain goal directed actions. Understanding that during this process of evolution which has resulted in achieving the baseline optimal performance and the establishment of the preferred cycle frequency, the skilled performers within the present study may have fully explored the action boundaries of the interacting constraints of the system dynamics.

Therefore, the skilled swimmers would not only have a highly stable coordinative state, but may also have exploited all the benefits of further practice at that specific

frequency i.e. repeated training at that frequency no longer elicits a training adaptation sufficient enough to cause a change in the organismic constraints. Consequently, it may be that the training undertaken within the present study was insufficient to perturb the coordinative structures and re-launch a search of the perceptual motor workspace. It may also be that the magnitude of the imposed constraint was insufficiently challenging to disturb the coordinative structure or provide a training stimulus which would cause adaptations to the organism (e.g. myogenic response), which in turn may cause a perturbation and or necessitate a rescaling of the existing pattern to accommodate the change in system dynamics.

Therefore, the observed reduction in MARP RMSE over the training and testing period, may signify that additional practice at the already established and entrained preferred EE_Hz may have only served to reinforce the coordinative state already adopted. Furthermore, it may be that only practice at different cycle frequencies and/or other training modalities which act to significantly perturb the coordinative state beyond a critical values at the established preferred cycle frequency, or result in an adaptation of the organismic constraints (i.e. strength / flexibility), may change the coordinative structure, and ultimately result in the adoption of a cycle frequency outwith the initial preferred cycle frequency as a consequence of changes in the UUS system dynamics.

If the initial (S0) UUS dynamics are considered as a (globally) sub-optimal state, with the assumption that higher levels of performance can be achieved with changes in coordination and/or organismic constraints; then this initial ordered state of the UUS dynamics is self organised and is (locally) optimised, with respect to a single or series of cost functions. Therefore, it may be that these cost function(s) around which

the current (local) state is optimised are not representative of the cost function required to optimise (globally) and may represent a naive UUS system dynamic (i.e. the system is optimising around a locally stable (preferred) cost function dictated by the boundaries of the interacting constraints. Similarly, further performance improvements/optimisation may only require that the already established pattern of behaviour is re-scaled to provide a more task specific coordinative structure.

Understanding that these are skilled athletes/performers, that this state of behaviour is locally optimised and given that the system has self organised in response to the current interacting constraints to achieve this behaviour, then the system dynamics may be seen to be globally sub-optimal with respect to achieving maximal levels of UUS performance. This globally sub-optimal state occurs either as a consequence of the optimisation evolving in response to an inappropriate cost function producing a naive coordination pattern, and/or, deficits/deficiencies in aspects of the organismic constraints (strength/flexibility/neural adaptation) and their interactions with the task and environmental constraints. As Holt, (1998) suggested, the idiosyncratic organismic constraints are all factors that affect the preferred cycle frequencies adopted and coordination patterns used to achieve them.

Therefore, the preferred cycle frequency may simultaneously represent the locally available optimal state and also a threshold / rate limiter for future performance enhancement, learning and coordination development in skilled age-group swimmers. Continual practice will only act to reinforce the already fully exploited attractor state and limit the opportunity to alter/shift away as the stimulus for change provided by practicing at the preferred frequency may no longer afford an

opportunity for change in the organismic constraints. Therefore, the efficacy of training at an already well established preferred cycle frequency for skilled age group swimmers may be limited as it does not provide a perturbation which sufficiently disturbs coordinative structure or provides a training stimulus.

Continuous relative phase variability – point by point RMSE

The point by point RMSE values from the CRP ensemble curves illustrate that certain points within the kick cycle are more tightly controlled (less variable) than others, and that the temporal structure of the variability is dependent on the coordinative structure observed. Both Foot v Shank and Heave v Pitch angle were much less variable at and around the start-end points of the kick cycle (figures 5.6 and 5.12). Whereas Foot v Thigh and Shank v Thigh demonstrated comparatively larger levels of variability at the start-end points with respect to the rest of the kick cycle (figures 5.8 and 5.10).

It might have been expected that minimal variability in the CRP plots would indicate a stable movement system, indicating a preference to maintain a particular coordination pattern (Balasubramaniam and Turvey, 2004). However, Wilson *et al.* (2008) have shown that certain coordinative structures apparent within the movement behaviour of skilled performers are found to vary substantially, suggesting that this variability enables other, more task specific coordinative structures to be more tightly controlled. It is also suggested that the change in magnitude of the variability around these coordinative structures is dependent on any change in the task dynamics/requirements (Wilson *et al.*, 2008; Schoner, 2002).

Therefore, it is suggested that as additional task constraints are imposed or removed (Freq Tested), the variability around certain key coordinative structures adapts to enable tighter control of relevant coordinative structures to meet the demands of the changing task. Balasubramaniam and Turvey (2004) suggested that the initial high or low levels of variability observed for a particular coordinative structure may alter, either as adaptations takes place and the system learns which coordinative structures need tighter control to optimise performance, or as a consequence of the inherent task dynamic. This may be apparent in the differences in the variability at the start/end points, with Foot v Thigh and Shank v Thigh both having comparatively higher variability than both Heave v Pitch angle and Foot v Shank. This suggests that the larger variability in the first two coordinative structures might enable the other two to be controlled more tightly. This would be appropriate for skilled UUS as both Foot v Shank and Heave v Pitch angle coordinative structures represent the control of the vortices shed into the wake and if timed correctly, energy recapture of previously shed vortices (Hochstein and Blickhan, 2011). Therefore, the increased levels of control associated with these two coordinative structures may be indicative of their importance to an understanding of UUS system dynamics and reflect the skill level of the participants.

There was a disparity in point by point RMSE between the fastest and slowest swimmers at the two Freq Tested. For Foot v Shank CRP the point by point RMSE was found to lower at an imposed frequency for the slower swimmers and higher for the fastest swimmers (irrespective of training group) (figure 5.6). In the Heave v Pitch angle CRP the slowest swimmers point by point RMSE was also found to be lower at an imposed frequency compared to preferred frequency (figure 5.12).

Both Schoner (2002) and Semjen (2000) have suggested that the within cycle variability/ stability present when learning a novel relative timing pattern at an imposed movement frequency, represents an 'anchoring' of key events. Swinnen *et al.* (1996) proposed that reversal points can be viewed as intermittent loci of control, or anchors for the organisation of the system. Schoner (2002) stated that these anchors are signified by the reduced variability and tighter control with respect to either relative or absolute timing. Therefore, questions still remain, regarding the variability structure for the CRP ensemble curves. Does the imposition of a cycle frequency act as an anchor causing decreased / increased variability around stable coordinative structures to maintain accuracy of an imposed frequency? Or is there task specific pattern stability which is attained irrespective of changes in task constraint (Balasubramaniam and Turvey, 2004)?

The point-by-point variability shown in the respective CRP figures (5.6, 5.8, 5.10 and 5.12) provides an indication of the initial (S0) state of the coordinative structures/ UUS system dynamics. The variability in the Foot v Shank CRP reveals that at the Imp Freq Tested the slowest swimmers had lower variability over the entire kick cycle when compared to their Pref Freq Tested, and the fastest swimmers variability was higher throughout the dorsal reversal section of the kick cycle in the Imp Freq Tested compared to the Pref Freq Tested. The variability in the Imp Freq Tested of the Heave v Pitch angle CRP shows the fastest swimmers with lower variability at the start/end points and higher variability throughout the dorsal reversal section when compared to the Pref Freq Tested. Slowest swimmers showed a similar pattern with a reduction in start/end point variability. However, the variability was

also lower through the dorsal reversal section of the kick cycle at the Imp Freq Tested.

The initial state of the Foot v Thigh CRP coordinative structure at Pref Freq Tested for Participant MS (the slowest swimmer), showed low variability at start/end points, suggesting that this coordinative structure was tightly controlled (figure 5.10). The start/end point variability at the Imp Freq Tested was greater, suggesting the imposed frequency is perturbing this coordinative structure. All the other swimmers (irrespective of group/performance level) had comparatively higher variability at the start/end point in both Freq Tested for Foot v Thigh CRP, with lower variability through the dorsal reversal section of the kick cycle. This may be indicative of a naïve form of coordination, with tighter control of an inappropriate coordinative structure.

As stated, one factor to consider which may limit performance is retaining modes of coordination which are entrained around sub-optimal states, i.e. those patterns which are tightly controlled/optimised with respect to the wrong cost function. Therefore, the success for the perturbation used to promote a search of the perceptual-motor workspace is dependent on the extent to which it can force the coordinative structure away from this current preferred coordinative state. One problem is that there may be a number of possible sub-optimal states for individuals and that one single method of perturbation cannot afford the opportunity to move away from a particular coordinative state around which they are currently anchoring their behaviour.

Consequently, coordination development might be best achieved by identifying the anchored behaviour(s) and employing methods which specifically act to shift those behaviours away from a sub-optimal state. Further analysis of a greater range of UUS abilities would enable any different UUS systems behaviour to be identified. And while Delignieres *et al.* (1998) recognised that the role of any intervention specifically designed to improve performance should not be limited to the promotion of the to-be-acquired pattern; an understanding of differences in the coordinative structures over the continuum of UUS skill level, and the individually dependent effects of a specific imposed task constraint can help determine which constraint to manipulate to facilitate a more expansive exploration of the perceptual-motor workspace. The initial disparity in point by point variability response between the fastest v slowest swimmers to the Freq Tested, suggested that the efficacy of the imposition of a cycle frequency may be dependent on the initial state of the individuals UUS system dynamics.

Understanding that the initial state of an individual's UUS system dynamics or coordinative structures might influence their interactions with a manipulation of the task constraints, then the efficacy of training at a preferred EE_Hz (preferred or imposed) is dependent on the state of the skilled swimmers locally optimised, time dependent UUS system dynamics. Therefore, continued practice at a self selected preferred EE_Hz or an imposed (preferred) EE_Hz may perturb the UUS system dynamics or act as a rate limiter/threshold dependent on initial conditions.

As there were no significant differences in max U, it could be construed that training at a preferred cycle frequency (either imposed or self selected) was preventing some

participants from developing an optimal search strategy and limiting the development of more appropriate solutions to the task. This is similar to the findings of Nourrit *et al.* (2000) where the required amplitude constraint imposed in the study acted to limit the development of a 'skilled' behaviour. Similarly, Wilson *et al.* (2008) have suggested that striving to minimise variability around a set pattern of coordination may inhibit performance development. So, if the act of imposition (imposed EE_Hz constraint) limits exploration of the perceptual-motor workspace then its efficacy may be confined to those individuals with specific, initial UUS system dynamics conditions. Therefore, the slower swimmers observed lower variability at an imposed (preferred) EE_Hz may (anchor) constrain the search for a more effective solution, whereas the same imposed constraint indicated higher variability in the fastest of the swimmers, suggesting greater levels of exploration.

Efficacy of coordinative structures as order parameters.

As stated at the beginning of this section, one of the main purposes of this study was to further examine the efficacy of the measured coordinative structures as order parameters which encapsulate the variations and relative contributions of all the ADF (Mitra *et al.,* 1998). Study two found that both Foot v Shank and Heave v Pitch angle were key determinants of UUS performance. In addition, it was observed that the movements at or around the knee were key to successful UUS performance, predicating the selection of Foot v Thigh and Shank v Thigh as representation of lower limb coordination. However, as Hong and Newell (2006b) and Vereijken *et al.* (1992, 1997) suggested, the increased complexity apparent with such complex multi degree of freedom systems makes establishing the relevant interactions between and

contributions of the coordinative structures to an understanding of system behaviour extremely difficult.

It could be argued that the Heave v Pitch angle coordinative structure provides a valuable representation of UUS system dynamics as it incorporates the end-effector commonly used to represent global system behaviour and coordination representing aspects of the local systems behaviour. However, further research is required to examine Heave v Pitch angle behaviour in relation to the other local behaviours at a synergistic level to determine any reciprocal relationships evident between local coordinative structures and the global UUS system dynamics, i.e. do they simultaneously regulate each other's behaviour (Haken *et al.,* 1985; Hong and Newell, 2006b)?

While all the coordinative structures measured with the present study provided insight into the adaptations to coordination in response to training and the imposed constraint, other coordinative structures may better represent UUS system dynamics. The behaviours observed in the four coordinative structures may only represent adaptations to enable another more appropriate coordinative structure(s) to be more tightly controlled. Therefore, more research is required over greater range of skill levels with a larger sample size and with different methods of perturbation to identify and accurately determine the efficacy of any order parameters used to describe and/or monitor the UUS system dynamics.

5.5 Conclusions

The first aim of the present study was to compare the effects of training at a preferred cycle frequency and an imposed (preferred) cycle frequency, on the kinematics and measures of coordination of UUS in skilled age-group swimmers. With no statistically significant change in max *U*, four weeks UUS training can be regarded as ineffective for performance enhancement, regardless of training modality employed. Significant differences in MARP of the Foot v Shank and Heave v Pitch angle were observed; suggesting training (irrespective of training group) had an effect on coordination. However, a more comprehensive analysis of the coordinative structures, comparing the discrete measures of coordination observed with the changes in variability (MARP RMSE) and the continuous measures of coordination, suggested that the practical significance of the statically significant differences are questionable. The findings are inconclusive, as changes may represent practically significant adaptation in coordination or simply be indicative of the functional variability apparent within the UUS system dynamics. What was apparent within the coordinative structures of the fastest and slowest swimmers was the idiosyncratic interactions with the imposed constraint (imposed frequency), suggesting that initial conditions of the UUS system dynamics influences the efficacy of the imposed constraint.

The second aim of the present study was to establish the efficacy of using the measured coordinative structures as an order parameter to encapsulate the USS system dynamics. The efficacy of the coordinative structures used to represent the UUS system dynamics is still inconclusive. While it can be argued that the Heave v Pitch angle provides valuable insight to UUS behaviour, its use as an order parameter

to encapsulate the UUS system dynamics and monitor adaptations in response to perturbation requires further, more detailed examination.

The third and forth aims of the present study were to determine the efficacy of imposed cycle frequency training for promoting learning and adaptation in both the local and global UUS system dynamics, and examine the act of frequency imposition to enable future studies delineate any effects of changing EE_Hz from the act imposition itself. The four week preferred cycle frequency (self selected or imposed) training intervention was inadequate to perturb the highly stable, entrained attractor states of the skilled performers swimming at their preferred cycle frequency by sufficient amount to cause a change in max *U*. In addition, the training interventions may not have provided an adequate training stimulus, (intensity and/or volume) which would result in adaptations to the organismic constraints.

Conversely, the skilled age-group swimmers analysed may have already learned to exploit fully the UUS system dynamics at their preferred cycle frequencies, suggesting that any additional training at a preferred cycle frequency would be ineffective in producing further changes in max *U*. However, the disparity in the variability between the fastest and slowest swimmers responses to the same imposed constraint (Imp Freq Tested) suggested that the initial conditions of the UUS system dynamics of an individual will dictate their interaction with the imposed preferred cycle frequency constraint. Therefore, the act of imposition itself can act as an additional constraint and needs to be considered when analysing future studies which impose higher and/or lower cycle frequencies.

Finally, understanding that the purpose of training can be regarded as a facilitation of further exploration away from sub-optimal preferred attractor states towards more task specific, higher order coordinative states rather than the promotion of a to-be-acquired pattern of movement (Thelen, 1986; Delignieres *et al.,* 1998), then any imposed constraint or training intervention needs to be sufficiently challenging to perturb the relevant coordinative structures to re-launch a search of the perceptual motor workspace. This renewed search can be accomplished either via a manipulation of a control variable to an appropriate magnitude which directly perturbs the coordinative structures and/or via a change in organismic constraints. Future research is required to determine which control variables and the magnitudes of manipulation are most effective for performance improvements in UUS.

Chapter 6

Summary, Conclusions, Limitations

&

Future Directions

6.1 Summary and Conclusions

The purpose of the present research was to (1) determine the reliability of the kinematic variables of UUS, (2) identify the key kinematic variables and measures of coordination, and (3) investigate the effects of the act of 'imposition' and efficacy of four weeks training at an imposed preferred cycle frequency for improving UUS performance in skilled age-group swimmers.

It was first necessary to calculate the reliability of the kinematic variables concerned with the execution of max *U* (Study 1). This was to ensure that any changes in these kinematic variables which occurred as a consequence of any future intervention could be identified as being outside the normal within-subject variation levels associated with this task. The aims of the first study were to: (1) determine the extent of any systematic bias between session, trial and/or cycle, (2) establish the within-subject (WS) variation of the key biomechanical measures commonly used to assess maximal UUS performance in skilled swimmers, and (3) ascertain the number of cycles/trials required to obtain stable levels of variability and high levels of reliability in the maximal UUS kinematics.

There was a systematic bias identified between the first data collection session and the remaining three sessions for max *U*, CL and EE_Hz, suggesting a learning effect as the skilled swimmers adapted to the novel UUS protocol. This systematic bias signified the requirement for a familiarisation session to ensure reliable kinematic data. No within or between trial systematic bias was found, indicating that swimmers were maintaining max *U* and associated kinematics throughout the data capture area

and that the number of trials performed and rest periods employed did not cause a level of fatigue sufficient enough to alter the kinematics. The WS CV% for the kinematic variables analysed ranged from 1.21% - 12.85% when calculated from the mean of three cycles. The CV% of all the nineteen kinematic variables was found to improve when the number of cycles used to calculate the mean value increased. The test-retest reliability undertaken to determine the number of cycles and trials required to obtain a stable level of variability and reliable kinematic data revealed all variable except knee JCA achieved an ICC>0.95 using the mean of six cycles, with the mean number of cycles required to achieve ICC>0.95 = 3.57 (± 2.09) cycles. It was concluded that six cycles provided a reliable representation of the UUS kinematic data. Even though knee JCA had not achieved an ICC>0.95 using six cycles, it had achieved an ICC>0.85 which is routinely accepted as reliable (Portney and Watkins, 2000).

Having established the number of cycles of data required to reliably represent the kinematic data, the levels of WS variability and the requirement for a familiarisation; the identification of the key kinematic variables and measures of coordination for predicting UUS performance in skilled age-group swimmers was undertaken (Study 2). The aims of the second study were to (1) examine which kinematic variables and measures of coordination provide the best predictive models for (a) EE_Hz (b) CL, and ultimately (c) max *U*; to enable a better understanding of the determinants of max *U* in skilled age group swimmers and (2) establish a rationale for which measure(s) of coordination could be used as an order parameter to enable an examination of the UUS system dynamics.

A total of eleven kinematic and coordination covariates predicted the variance in EE_Hz and CL. The final parsimonious BE ANCOVA model revealed two covariates; knee-ankle wave velocity and max knee angle velocity predicted a significant proportion of the variance in max *U*. The fixed factor (Participant) significantly contributed to the model. However, when participant was removed the predictive quality reduced substantially, indicating a reduction in the explained variance from 94.4% down to 53.5%.

The reduction in explained variance with the removal of the participant as a fixed factor signified that the between participant variability explained a significant proportion of max *U*. Consequently, the simultaneously competing factors of maximising propulsion and minimisation of AD with the same movements, coupled with the interactions with the swimmers' individual organismic constraints, suggests that a number of different solutions are available to meet the requirements of the motor problem. Therefore, individual swimmers' idiosyncratic UUS techniques are an important factor to be considered in an understanding of the production of max *U*.

However, while the individuals' techniques were found to influence the production of max *U*, the identified predictive qualities of the two variables suggest that the motion at and around the knee were important to the production of max *U* within skilled age-group swimmers. Therefore, it was concluded that the successful transmission of the propulsive waveform along the knee to ankle section of the swimming body was important for max *U* production in skilled age group. The anatomical limitations of the knee joint impact on the effectiveness with which the

undulatory motions can act to minimise flow separation and/or recapture and reuse energy previously shed into the body wake (Ungerechts, 1982). Consequently, the AoA and Heave v Pitch angle CRP values were consistently outside the 15°-25° AoA range at which optimal levels of thrust are produced (Sfakiotakis *et al.*, 1999; Videler and Kamermans, 1985; Triantafyllou *et al.*, 1993) and much higher than the 75° optimal phase relationship at which the maximisation of propulsion and simultaneous minimisation of AD found for highly effective aquatic animals (Anderson *et al.*, 1998). In excess of 90% of the total UUS cycle time was spent outside the proposed optimal range for AoA. However, future research is required to determine if the changes in AoA and Heave v Pitch angle CRP values observed within a kick cycle are representative of: (1) the maximisation of percentage time spent in the optimally defined range in response to morphological constraints, (2) the optimisation of vortex-recapturing to minimise AD and enhance propulsive impulse, or (3) the balance between the previous two mechanisms for UUS optimisation.

The range of movement achieved at the knee (and its temporal structure) in relation to the undulatory movement of the body as a whole, determines the extent of the amplitude at the ankle/end-effector. Therefore, given the findings of the final BE ANCOVA model for max U and the previous empirical evidence (Ungerechts, 2000; Hochstein and Blickhan, 2011; Hochstein *et al.*, 2012; Cohen *et al.*, 2012) regarding the importance of movement at or around the knee; the CRP of Foot v Shank, Foot v Thigh and Shank v Thigh were include in Study 3 to determine their efficacy for use as order parameters to capture the state of the UUS system dynamics.

Having identified the key determinants of EE_Hz, CL and max *U* in UUS performance of skilled age-group swimmers, the research then focused on examining the effects of an imposed frequency. The aims of the third study were to: (1) compare the effects of training at a preferred cycle frequency and an imposed preferred cycle frequency, on the kinematics and measures of coordination of UUS in skilled age-group swimmers, (2) establish the efficacy of using the measured coordinative structures as order parameters to encapsulate the USS system dynamics, (3) determine the efficacy of imposed cycle frequency training for promoting learning and adaptation in both the local and global UUS system dynamics, and (4) examine the act of frequency imposition to determine its effects to enable future studies delineate any effects frequency imposed from the act imposition itself.

There were no statistically significant effects of training at an imposed preferred cycle frequency on any of the discrete kinematic variables or measures of coordination. Most importantly, no change in max *U* was observed over the training and testing period, suggesting that four weeks imposed preferred frequency training was ineffective as a means of performance enhancement. There were significant differences identified by Freq Tested x Session and Session, signifying that irrespective of training modality employed adaptations in kinematics and measures of coordination occurred. The majority of the Freq Tested x Session significant results identified occurred in response to the PGp adapting to the imposition of a preferred cycle frequency over the course of the training and testing period. What cannot be delineated is whether this occurred in response to the preferred frequency

training undertaken or an increased familiarisation with the imposed frequency protocol as a consequence of repeated testing.

The two of coordinative structures (MARP Foot v Shank and MARP Heave v Pitch angle) used to represent the UUS system dynamics were shown to be statistically different by Session, irrespective of training group. Changes in coordination can be representative of an exploration of the action boundaries or response to perturbation. However, the practical significance of the levels of change observed was questionable as the variability in MARP for both these measures were observed to decrease from S0 as a consequence of training, enabling smaller differences between Session to be identified as statistically significant. Analysis of these statistically significant changes in conjunction with the other measures of MARP variability (MARP RMSE) and the CRP data suggested that the differences observed in MARP Foot v Shank and MARP Heave v Pitch angle may not represent practically significant changes in UUS system dynamics. It could be argued that the Heave v Pitch angle coordinative structure provides a valuable representation of UUS system dynamics as it incorporates the end-effector commonly used to represent global system behaviour and coordination representing aspects of the local systems behaviour. However, further research is required to examine Heave v Pitch angle behaviour in relation to the other local behaviours at a synergistic level to determine any reciprocal relationships evident between local coordinative structures and the global UUS system dynamics, i.e. do they simultaneously regulate and are regulated by each other (Haken *et al.,* 1985; Hong and Newell, 2006b).

This further research is required to determine the efficacy as while there were identified changes in the coordinative structures of both the fastest and slowest swimmers presented, max *U* was maintained throughout the training and testing period. With no significant change in max *U* in either the PGp or IGp, the magnitude of the re-scaling of the CRP patterns may only reflect the functional variability contained within the skilled swimmers UUS system dynamics, with the abundant ADF enabling performance levels to be maintained despite any perturbation caused by training intervention.

Another interpretation of the data presented suggests that training at a preferred cycle frequency either self selected or imposed may not be effective for skilled swimmers as they have already learned to exploit fully the system dynamics at that frequency. Also, having fully exploited the system dynamics at that preferred frequency, repeated practice at that frequency (at the levels employed within the present study) may no longer elicit a training response, i.e. adaptation in organismic properties. Therefore, continued practice at that frequency would only serve to reinforce the movement behaviours achieved at that frequency, as observed in the reduced variability in MARP data.

However, also apparent within the CRP variability data was an indication that the initial conditions (individual initial UUS system dynamics) resulted in different interactions with the same imposed constraint, with the variability of the fastest and slowest swimmers presented illustrating variations in the magnitude and location of variability in response to the respective Freq Tested. The disparities apparent in the

variability at the suggests that that certain sections of the kick cycle were being more or less tightly controlled or anchored, with other coordinative structures being more variable. Further research is required to establish if the increased variability in one coordinative structure is related to the anchoring of other key behaviours, and if certain anchored behaviours are representative of naive coordinative structure behaviour within the UUS system dynamics.

The coordinative structures measured with the present study show adaptations to coordination in response to training and the imposed constraint. However, other coordinative structures may better represent UUS system dynamics. The behaviours observed may only represent adaptations which enable another more appropriate coordinative structure(s) (which have not been measured) to be more tightly controlled. Therefore, more research is required over greater range of skill levels with a larger sample size and with different methods of perturbation to identify and accurately determine the efficacy of any order parameters used to describe and/or monitor the UUS system dynamics.

The efficacy of imposed preferred frequency training to promote a search of the perceptual-motor workspace will be better understood when additional research is performed which examines the magnitude of any changes in MARP and CRP and their respective variability/stability behaviour in response to imposed higher and/or lower cycle frequencies. By comparing the extent of changes and the UUS system dynamics responses, a more complete picture of the efficacy of imposed preferred

frequency training to promote learning and adaptation could be determined and the full extent of the act of imposition established.

6.2 Limitations

It was concluded from the present investigation that there were no changes in the discrete kinematics or measures of coordination as a consequence of training at an imposed cycle frequency. However, adaptations in the kinematics and/or coordination may have occurred if the training period continued beyond the four weeks employed within the present study. The re-scaling of the CRP observed may have eventually resulted in noticeable improvements in performance and/or passed beyond a critical level and shifted to a new stable pattern of coordination.

Moreover, the other swim training undertaken by the participants within the nine week training and testing period was only controlled with respect to the exclusion of any kicking practice outside of the experimental UUS training programme. The study was undertaken during the swimmers off season, with swimming training (volume and intensity) in a maintenance phase to prevent detraining. Therefore, while the effects of fluctuations in training intensity and volume were minimised, other training factors may have influenced the results of the present study. While, this may limit the representative qualities of the data presented, the situation does correspond to the normal practice of athlete training, were no single factor is worked on in total isolation.

While the present study represented a more substantial time period over which repeated measurements of kinematics and coordination are recorded, the data still only represents a series of snapshots of UUS system dynamics. As such, the stability of the coordinative structures was only inferred from the changes in variability over the training and testing period. This does not represent a true account of the respective coordinative structures attractor state dynamics, as no kinematic/coordination measures were recorded during the training undertaken. Therefore the evolution of any changes which may have manifested during the individual training sessions could not be determined. Similarly, the experimental protocol employed, whereby the perturbed state (Imp Freq Tested) and the preferred state (Pref Freq Tested) were analysed within separate trials. To determine the effects of a specific perturbation, examinations of critical fluctuations, critical slowing down/relaxation times, etc are routinely performed to determine the attractor state dynamics (Schloz, *et al.,* 1987). The methods employed with the present study could not afford the opportunity to examine these important factors.

It is also important to consider that the results presented within this thesis are limited to the sample population used. Improvement in max U and associated changes in kinematics and measures of coordination may have occurred if the research had been completed with more or less skilled swimmers. The homogeneity of the sample used in the present study is also in question. While the sample population were homogenous in relation to training and competitive experience there was a significant disparity apparent between the fastest and slowest values of max U.

6.3 Future Directions

Having established the effects of the act of imposition, research is required to examine the efficacy of the imposition of, and training at higher and lower cycle frequencies for improving max *U*. Examining an imposed higher or lower cycle frequency over a similar, or longer period of training, would determine their efficacy as appropriate training interventions and provide additional information regarding the UUS system dynamics. Given the increasing requirement for and popularity of land based strength and conditioning training within skilled swimmers training programmes (Newton *et al.,* 2002), it would be worthwhile examining the efficacy of other commonly employed training interventions which specifically target organismic constraints (strength and flexibility). This research, in combination with the imposed frequency studies would provide valuable information regarding the most effective methods for perturbing UUS system dynamics to re-launch the search of the perceptual-motor workspace.

The continued investigation of UUS using non-linear analysis methods to determine the evolution of behaviour and examine the stochastic and deterministic elements of the variability structure would provide a more detailed account of UUS system dynamics. However, these methods require a substantial increase in the number of data points used to represent system behaviour compared to those used in the present studies. (Kochi *et al.,* 2008). The continued development and improvements in marking tracking software providing greater automation of the data collection process would allow more detailed analysis of kinematic and coordination changes, with variability and stability being observed with the use of more complex and

accurate 3D protocols. The development of automated data capture systems such as Vicon and Qualisys for use in an aquatic environment will eventually enable much larger data sets (participant numbers, repeated trials and longer training interventions) to be more easily collected and processed. The increased capture rate will also enable more complex non linear analysis methods (approximate entropy/recurrence quantification analysis) to be employed.

Unfortunately, given the constraints of working in an aquatic environment it would be unrealistic to try and determine the real-time attractor state dynamics (critical fluctuations, relaxation times, etc) for UUS. The requirement to breath-hold during the maximal UUS trial and the limited time spent underwater would restrict the potential to reach max *U* at an imposed cycle frequency, remove the imposed cycle frequency perturbation and monitor the UUS system dynamics, to establish if and how the behaviour returns to a stable attractor state. Therefore, other maximal cyclical activities such as rowing or kayak ergometry could be employed and investigated to determine their respective system dynamics following systematic perturbation with an imposed cycle frequency over an extended training period.

Finally, the investigation of a larger and more heterogeneous population with a greater range of UUS skill level would enable a more detailed examination of the efficacy of the predictive qualities of the key variables for the production of max *U* identified in Study 2. If sufficiently large sample size could be achieved within the various sub-sets (skill levels) of the population can be recorded, investigations can then begin to determine which factors are common to the respective subsets and if

any of UUS system dynamics are acting as rate limiters restricting development of appropriate coordinative structures and ultimately UUS performance.

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Appendix 1

care
Centre for Aquatics Research & Education
Director: Professor Ross Sanders r.sanders@ed.ac.uk

Informed Consent

Dear Swimmer/Parent,

We are seeking your participation in a research study, which will examine the reliability of undulatory underwater swimming performance. This study will assess swimming movements during an underwater swimming task. Your participation in this study will be on a voluntary basis. If you agree to participate you will be asked to swim 5 x 15m underwater trials at maximal speed using the dolphin leg kick. This process will be repeated four times, with a one week time interval between testing sessions. Between testing sessions you will undertake no underwater undulatory swimming training as part of your normal training schedule.

Potential benefits from this analysis include a better understanding of swimming techniques, which may lead to improved methods for swimming training.

If you have read and understood the requirements of your participation in the research study and do not have any further questions regarding the study, please read the following and print and sign the form to indicate your informed consent.

I, _____ (clearly print YOUR name), agree to participate in an analysis of swimming biomechanics and coordination.

I understand that to participate, I will be observed and videotaped during a scheduled session. The research team will apply oil based face paint to anatomical landmarks for purposes of digitizing.

I am aware that the research team will keep the video data. It has been explained to me that this data will be assigned a number and kept separate from the consent forms, thus ensuring that all data will be anonymous and confidential. Furthermore it has been explained that, once the data is processed, it will be electronically stored and protected by the research team. The results will be aggregated (i.e., stored as averages), and if the study is publicly disseminated through publication, it will not be possible to identify myself or anyone else who participated in the study.

I am aware that I have the right to not participate and that I may discontinue at any time. Furthermore, I understand that my participation in the analysis is not in response to financial or other inducements.

I have had the unique features of this swimming pool explained to me and I am aware of the additional risks associated with swimming in a swimming pool.

I DO / DO NOT grant permission to be recorded by video cameras

I DO / DO NOT grant permission for the video recordings to be shown to others for educational purposes, for example, on the World Wide Web.

Signature: **Date:**

If under 18 years please get your parent/guardian to print and sign below:

Print Name: **Signature:** **Date:**

Appendix 2

care
Centre for Aquatics Research & Education
Director: Professor Ross Sanders r.sanders@ed.ac.uk

Underwater Kicking Study

Dear Swimmer,

This study is investigating the swimming performance levels achieved and the consistency of the swimming movements that skilled swimmers employ when swimming maximally underwater using the dolphin kick. The study involves repeated testing throughout the period of the research.

Prior to starting the study swimmers will be fully briefed as to the nature of the research, the task to be undertaken, the layout of the pool and the safety concerns regarding the pool. Informed consent will also be required before swimmers can participate in the study.

Before starting the first testing session the swimmers' height, weight and limb lengths will be recorded.

The study is conducted over a period of four weeks. Each testing session consists of swimming five maximal efforts of 15m of underwater swimming using the dolphin leg kick. Five minutes rest is allowed between each maximal effort. A standardised warm-up is conducted prior to starting each testing session. The first session should take between 45-60 minutes (additional time required to take all the height, weight, and limb length measurements); thereafter each session should take less than 30 minutes. Large numbers of swimmers can be filmed concurrently. While one swimmer is resting another can be filmed.

Appendix 3

Centre for Aquatics Research & Education
Director: Professor Ross Sanders r.sanders@ed.ac.uk

Informed Consent

Dear Swimmer/Parent,

We are seeking your participation in a research study, which will determine the most important factors for maximal undulatory underwater swimming performance. This study will assess swimming movements during an underwater swimming task. Your participation in this study will be on a voluntary basis. If you agree to participate you will be asked to swim 3 x 15m underwater trials at maximal speed using the dolphin leg kick.

Potential benefits from this analysis include a better understanding of swimming techniques, which may lead to improved methods for swimming training.

If you have read and understood the requirements of your participation in the research study and do not have any further questions regarding the study, please read the following and print and sign the form to indicate your informed consent.

I, _____ (clearly print YOUR name), agree to participate in an analysis of swimming biomechanics and coordination.

I understand that to participate, I will be observed and videotaped during a scheduled session. The research team will apply oil based face paint to anatomical landmarks for purposes of digitizing.

I am aware that the research team will keep the video data. It has been explained to me that this data will be assigned a number and kept separate from the consent forms, thus ensuring that all data will be anonymous and confidential. Furthermore it has been explained that, once the data is processed, it will be electronically stored and protected by the research team. The results will be aggregated (i.e., stored as averages), and if the study is publicly disseminated through publication, it will not be possible to identify myself or anyone else who participated in the study.

I am aware that I have the right to not participate and that I may discontinue at any time. Furthermore, I understand that my participation in the analysis is not in response to financial or other inducements.

I have had the unique features of this swimming pool explained to me and I am aware of the additional risks associated with swimming in a swimming pool.

I DO / DO NOT grant permission to be recorded by video cameras

I DO / DO NOT grant permission for the video recordings to be shown to others for educational purposes, for example, on the World Wide Web.

Signature: **Date:**

If under 18 years please get your parent/guardian to print and sign below:

Print Name: **Signature:** **Date:**

Appendix 4

care
THE UNIVERSITY OF EDINBURGH
Centre for Aquatics Research & Education
Director: Professor Ross Sanders r.sanders@ed.ac.uk

Underwater Kicking Study

Dear Swimmer,

This study is investigating the most important factors for maximal undulatory underwater swimming performance.

Prior to starting the study swimmers will be fully briefed as to the nature of the research, the task to be undertaken, the layout of the pool and the safety concerns regarding the pool. Informed consent will also be required before swimmers can participate in the study.

Before starting the first testing session the swimmers' height, weight and limb lengths will be recorded.

The study is conducted over a single session. This testing session consists of swimming three maximal efforts of 15m of underwater swimming using the dolphin leg kick. Five minutes rest is allowed between each maximal effort. A standardised warm-up is conducted prior to starting the testing session. The testing session should take between 45-60 minutes (additional time required to take all the height, weight, and limb length measurements

Large numbers of swimmers can be filmed concurrently. While one swimmer is resting another can be filmed.

Appendix 5

Centre for Aquatics Research & Education
Director: Professor Ross Sanders r.sanders@ed.ac.uk

Informed Consent

Dear Swimmer/Parent,

We are seeking your participation in a research study, which will examine swimming performance and co-ordination. This study will assess swimming skill during an underwater swimming task. Your participation in this study will be on a voluntary basis. If you agree to participate you will be asked to swim 6 x 15m underwater trials at maximal speed using the dolphin leg kick. This process will be repeated several times, with a one week time interval between testing sessions. Between testing sessions you will undertake regular training as part of your normal training schedule – this will include specific training drills related to this study.

Potential benefits from this analysis include a better understanding of swimming techniques, which may lead to improved methods for swimming training.

If you have read and understood the requirements of your participation in the research study and do not have any further questions regarding the study, please read the following and print and sign the form to indicate your informed consent.

I, _____ (clearly print YOUR name), agree to participate in an analysis of swimming biomechanics and coordination.

I understand that to participate, I will be observed and videotaped during a scheduled session. The research team will apply oil based face paint to anatomical landmarks for purposes of digitizing.

I am aware that the research team will keep the video data. It has been explained to me that this data will be assigned a number and kept separate from the consent forms, thus ensuring that all data will be anonymous and confidential. Furthermore it has been explained that, once the data is processed, it will be electronically stored and protected by the research team. The results will be aggregated (i.e., stored as averages), and if the study is publicly disseminated through publication, it will not be possible to identify myself or anyone else who participated in the study.

I am aware that I have the right to not participate and that I may discontinue at any time. Furthermore, I understand that my participation in the analysis is not in response to financial or other inducements.

I have had the unique features of this swimming pool explained to me and I am aware of the additional risks associated with swimming in a swimming pool.

I DO / DO NOT grant permission to be recorded by video cameras

I DO / DO NOT grant permission for the video recordings to be shown to others for educational purposes, for example, on the World Wide Web.

Signature: **Date:**

If under 18 years please get your parent/guardian to print and sign below:

Print Name: **Signature:** **Date:**

Appendix 6

care
THE UNIVERSITY OF EDINBURGH
Centre for Aquatics Research & Education
Director: Professor Ross Sanders r.sanders@ed.ac.uk

Underwater Kicking Study

Dear Swimmer,

This study is investigating the swimming performance levels achieved and the co-ordination that skilled swimmers employ when swimming maximally underwater using the dolphin kick, at an imposed kicking frequency. This research is a training study which is designed to examine the process of optimisation of performance of the underwater dolphin kick. The study involves repeated testing throughout the period of the programme, and continually training (within your normal training sessions).

Prior to starting the study swimmers will be fully briefed as to the nature of the research, the task to be undertaken, the layout of the pool and the safety concerns regarding the pool. Informed consent will also be required before swimmers can participate in the study.

Before starting the first testing session the swimmers' height, weight and limb lengths will be recorded.

The study is conducted over a period of eight weeks. Each testing session consists of swimming six maximal efforts of 15m of underwater swimming using the dolphin leg kick (3 at you own self selected/preferred frequency and 3 at an imposed frequency). Five minutes rest is allowed between each maximal effort. A standardised warm-up is conducted prior to starting each testing session. The first session should take between 45-60 minutes (additional time required to take all the height, weight, and limb length measurements); thereafter each session should take less than 30 minutes. Large numbers of swimmers can be filmed concurrently. While one swimmer is resting another can be filmed.

Appendix 7

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THE UNIVERSITY OF EDINBURGH
Centre for Aquatics Research & Education
Director: Professor Ross Sanders r.sanders@ed.ac.uk

Warrender Swimming Club Provisional Timetable

Test Number	Date & Time	Purpose	Comments	Additional Details
Familiarisation	**28th Jan**	• Practice experimental protocol		
Preferred Hz Assessment	**4th Feb**	• Determine preferred Hz		
Test 0	**25th Feb**	• 3 trials preferred frequency kick • 3 trials imposed frequency kick	• Swimmers splint in to Groups based on the level of imposed frequency • Test to establish initial effects of an imposed frequency • Training commences after this testing session • 3 times a week	• See attached sheet for training details
Test 1	**4th March**	• 3 trials preferred frequency kick • 3 trials imposed frequency kick	• Training in 3 sessions	
Test 2	**11th March**	• 3 trials preferred frequency kick • 3 trials imposed frequency kick	• Training in 3 sessions	
Test 3	**18th March**	• 3 trials preferred frequency kick • 3 trials imposed frequency kick	• Training in 3 sessions	
Test 4	**25th March**	• 3 trials preferred frequency kick • 3 trials imposed frequency kick	• Training in 3 sessions	
	2 Week Break		• No UUS training in this period •	
Re-test	**8th April**	• 3 trials preferred frequency kick • 3 trials imposed frequency kick	• End of Study	